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Inventory of facilities, technical specifications and experiment portfolio

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GEOLAB

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Executive Summary

The GEOLAB Research Infrastructure (RI) consists of 11 testing facilities in Europe aimed to study the ground behavior in its interaction with structural Critical Infrastructure (CI) elements and the environment. The overarching aim of GEOLAB is to allow the European geotechnical community using these key national research infrastructures to perform research and innovation to address challenges faced by the CI in Europe.

With this general aim, this document collects a comprehensive description of each infrastructure - its scope, physical description, technical specifications, existing tools, available instrumentation, software for data management, a portfolio of each facility, an overview of the problems that can be explored with the facility and details of some project examples.

As a summary, Table 1 presents some basic information of the facilities.

Table 1 Basic information about all the facilities

Name of the facility	Country/City	Owner
Large-scale triaxial apparatus	Slovenia / Ljubljana	UM/ZAG
TU Delft Geotechnical centrifuge	The Netherlands / Delft	TU Delft
Beam and Drum Centrifuge	Switzerland / Zurich	ETHZ
TU Delft Large Scale Geotechnical Physical Modelling Facility	The Netherlands / Delft	TU Delft
Uni-Eiffel Geo-Centrifuge	France / Bouguenais	Uni Eiffel
GeoModel Container	The Netherlands / Delft	Deltares
Geo-Centrifuge	The Netherlands / Delft	Deltares
Schofield Centre	United Kingdom / Cambridge	UCAM
TUDa Geotechnical Test Pit	Germany / Darmstadt	TUDa
CEDEX Track Box	Spain / Madrid	CEDEX
Geo-Test Sites	Norway / Onsøy, Tiller, Halden, Øysand and Svalbard	NGI

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List of Abbreviations

AI	Artificial Intelligence
CI	Critical Infrastructure
CA	Consortium Agreement
DOI	Digital Object Identifiers
DMP	Data Management Plan
ERA	European Research Area
FAIR	Findable, Accessible, Interoperable and Reusable
IAB	International Advisory Board
ICT	Information and Communication Technology
IP	Intellectual Property
JIP	Joint Industry Project
JRA	Joint Research Activitie(s)
MT	Management Team
NA	Networking Activitie(s)
NG	Next Generation
PGA	Participants General Assembly
RI	Research Infrastructure
SME	Small and Medium Enterprise(s)
TA	Transnational Access
TRL	Technology Readiness Level
USP	User Select Panel

1 Introduction

1.1 About GEOLAB

The existing Critical Infrastructure (CI) of Europe in the water, energy, urban and transport sector is facing major challenges because of pressures such as climate change, extreme weather, geo-hazards, aging and increased usage in combination with pivotal changes in the CI to meet long-term societal goals (e.g. energy transition). To address these challenges, scientific research and innovative solutions are needed that can only be achieved by an interdisciplinary, cross-boundary approach and by equipping expert teams with the most advanced suite of physical research infrastructure available that allows them to work across spatial scales, explore different theories that describe the pressures and adopt innovative techniques for solutions.

The GEOLAB Research Infrastructure (RI) consists of 11 unique installations in Europe aimed to study subsurface behavior and the interaction with structural CI elements (e.g. a bridge) and the environment. The overarching aim of GEOLAB is to integrate and advance these key national research infrastructures towards a one-stop-shop of excellent physical research infrastructure for performing ground-breaking research and innovation to address challenges faced by the Critical Infrastructure of Europe.

During the Joint Research Activities (JRA), the capabilities of the integrated GEOLAB RI services are improved beyond present state-of-the-art. Topics are: (1) Harmonizing operation (2) Advancing physical modelling of the impact of climate change, aging and extreme events on CI; (3) Development of 3D-4D measurement techniques; (4) Application of new materials and new sensing techniques; (5) Data management of performed experiments for future re-use.

During Transnational Access (TA), users outside the consortium gain access to the GEOLAB installations to perform research and innovation. The scientific research community will use the enhanced capabilities of GEOLAB from the JRA to perform ground-breaking experiments. For CI managers and policy makers, the activities will result in a more comprehensive understanding of the challenges facing CI and evidence to base decision making upon. The construction industry will use GEOLAB to proof innovative solutions for the CI and so gain more leadership in the industrial and enabling technologies.

There will be close interaction with Small and Medium-sized Enterprises (SME) that develop user-friendly engineering software from numerical modelling advances which are validated in the TA projects. We will explicitly challenge SME on sensing, new materials and other niches for innovative solutions, which will have spinoff in other fields of application, contributing to the competitiveness of Europe.

Networking Activities (NA) are another core element of GEOLAB, culminating in workshops and other outreach events that foster a digital and In Real Life community, thereby providing a productive channel to communicate with different stakeholder groups.

The GEOLAB consortium is a collaboration of renowned organizations coordinated by Deltares (the Netherlands). Other consortium partners are: CEDEX Spain, NGI Norway, University of Cambridge (United Kingdom), Delft University of Technology (the Netherlands), University of Maribor (Slovenia), Technical University Darmstadt (Germany), ETH Zürich (Switzerland), Université Gustave Eiffel (France) and KPMG Future Analytics (Ireland).

More information: www.project-geolab.eu.

1.2 Document content

This document collects a comprehensive description of each GEOLAB facility, to help potential users of Transnational Access to understand their capabilities and limitations when deciding to perform research and innovation in the installations. Each description includes the following aspects:

- Basic information.
- Scope of the facility.
- Physical description and technical specifications.
- Sensors and instrumentation used in the facility.
- Test description.
- Examples of results.
- Relevant projects performed in the facility.
- Reference papers.

GEOLAB project comprises 11 installations situated in 8 European countries, as shown in Figure 1. The installations can be ordered according to the scale of the experiments, from laboratory to field scale, as shown in Figure 2.

Figure 1 Location of each facility

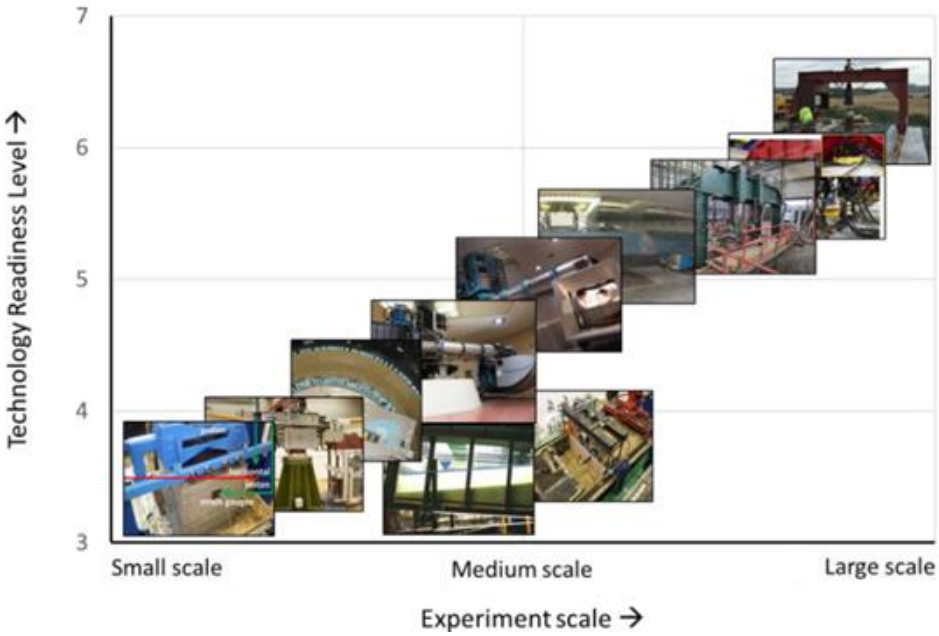


Figure 2 GEOLAB facilities ordered by the scale of the experiments

As a summary, Table 2 presents some basic information about the facilities.

Table 2 Basic information of each facility

Name of the facility	Country/City	Owner	Scope
Large-scale triaxial apparatus	Slovenia / Ljubljana	UM/ZAG	Mechanical testing of various geomaterials and their interactions with synchronized vertical-horizontal monotonic/cyclic loading
TU Delft Geotechnical centrifuge	The Netherlands / Delft	TU Delft	Small scale physical modelling of various geotechnical engineering systems at an enhanced gravitational field.
Beam and Drum Centrifuge	Switzerland / Zurich	ETHZ	Physical modelling to investigate rainfall-induced landslides, in situ installations and testing and soil structure interaction under static and dynamic loading
TU Delft Large Scale Geotechnical Physical Modelling Facility	The Netherlands / Delft	TU Delft	Large scale physical modelling of various geotechnical problems at 1g.
Uni-Eiffel Geo-Centrifuge	France / Bouguenais	Uni Eiffel	Physical Modelling Facility for geotechnical engineering systems at small scale
GeoModel Container	The Netherlands / Delft	Deltares	Studying soil behaviour and the interaction with structures
Geo-Centrifuge	The Netherlands / Delft	Deltares	Testing physical scale models of geotechnical engineering systems
Schofield Centre	United Kingdom / Cambridge	UCAM	Geotechnical process and construction modelling
TUDa Geotechnical Test Pit	Germany / Darmstadt	TUDa	Study of soil-structure interaction and other geotechnical problems

Name of the facility	Country/City	Owner	Scope
CEDEX Track Box	Spain / Madrid	CEDEX	Tests on railway infrastructure for geotechnical proposes
Geo-Test Sites	Norway / Onsøy, Tiller, Halden, Øysand and Svalbard	NGI	Full-scale field experiments for testing and verifying innovative soil investigation methods and prototypes of geotechnical structures

The information collected in this document is also available on the project website for easy access and quick reference. The GEOLAB website can be accessed here: www.project-geolab.eu

2 Large-scale triaxial apparatus (UM/ZAG)

2.1 Basic information

Table 3 collects some basic information about the facility.

Table 3 Basic information of the large-scale triaxial facility, which enables also traffic load simulations

Large-scale triaxial apparatus	
Name (short)	Large-scale triaxial apparatus
Name (long)	Large-scale triaxial apparatus
Owner	Slovenian National Building and Civil Engineering Institute (ZAG)
Location (City/Country)	Ljubljana/Slovenia
Address	Dimičeva ulica 12, SI-1000 Ljubljana, Slovenia
Website (vernacular language)	http://www.zag.si/en/equipment
Website (English)	http://www.zag.si/en/equipment
Contact (e-mail)	stanislav.lenart@zag.si
Head of facility (name/e-mail)	Stanislav Lenart / stanislav.lenart@zag.si
Construction year	2014

2.2 Scope of the facility

Traffic Load Simulator is a part of the large-scale triaxial apparatus at the Slovenian National Building and Civil Engineering Institute (ZAG). Its main purpose is to enable mechanical testing of various geomaterials and their interaction among themselves. Thanks to the very high accuracy level of load/displacement control and measurements, characterization of material (e.g. stiffness, damping etc.) at very small strain ranges are possible.

With some limitations mentioned in the following paragraphs, the facility enables testing of geomaterials in triaxial, direct shear and simple shear mode. Furthermore, custom made loading of the specimen (e.g. principal stress rotation) is possible.

2.3 Facility physical description / Technical specifications

The large-scale triaxial apparatus at the Slovenian National Building and Civil Engineering Institute (ZAG) has capability of axial and horizontal loading of prismatic specimens with height up to 80 cm and cross section 40 cm x 40 cm. It can be used in triaxial, direct shear or simple shear loading mode. Monotonic or cyclic loading tests can be performed.

Specimen is installed within the rubber membrane. The confining pressure is applied by means of a partial vacuum, as back pressure and it is thus limited to 100 kPa (up to approximately 85 kPa in reality). Seventeen rigid confining aluminium frames each with a height of 3 cm are used for simple shear mode, enabling K_0 stress state during the axial loading. The axial and horizontal loading device employs electro-hydraulic actuators with a capacity of 100 kN and 200 kN, respectively. The axial load is measured by means of two load cells attached successively at the top cap, in order to eliminate the effects of piston friction. The load cells have different capacities. The first one (with higher accuracy) is to be used for measurements within low load range (up to 10 kN), while the second one is to be used out of this range. The first load cell is mechanically protected such that when the load exceeds its range, the measurements are performed by the second one. Axial and lateral strains are measured by linear variable displacement transducers placed in various positions on the specimen. Measurements of local small strains (up to 10^{-5}) in both directions are enabled. Furthermore, accelerometers can be attached on the specimen to measure transmission (velocities) of shear waves through it. Optical system (GOM Aramis) for displacement measurements can be used during the specimen loading as well.

The capability of a simple shear apparatus can be used also to apply the loading with controlled principal stress axes rotation. Lateral confinement of test specimen makes it possible to keep the cross-sectional area of the specimen constant, thus representing a K_0 stress state during the axial loading. The installation of different layers of specimen inside the confining frames (e.g. the unbound granular material and the asphalt layer) and application of synchronized vertical and horizontal cyclic loads to the specimen enables the simulation of specific characteristics of traffic loading without a moving wheel.

A drawing of general testing device setup is showcased in Figure 3.

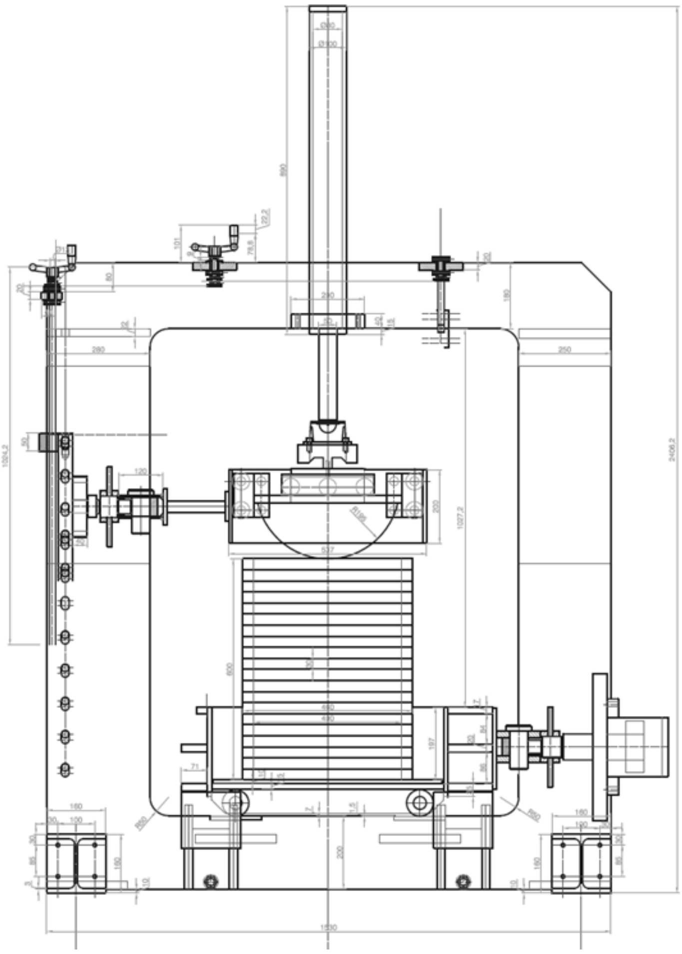


Figure 3 General arrangement of the testing device at Slovenian National Building and Civil Engineering Institute (ZAG)

An overview of the systems, utilities and equipment that are available for the large-scale triaxial apparatus is given in Table 4 together with a brief description of their technical specifications.

Table 4 Overview of the large-scale triaxial apparatus setup

Systems/Utilities/Equipments	Description
Loading frame	Enables prismatic specimens, maximum height of 80 cm and cross section 40 cm x 40 cm
Axial loading piston	Hydraulic piston with capacity 100 kN (or 200 kN), max displacement 800 mm

Systems/Utilities/Equipments	Description
Horizontal loading piston	Hydraulic piston with capacity 200 kN (or 100 kN), max displacement 100 mm, load is applied at the bottom of prismatic specimen
Confining pressure	Confining pressure is applied by means of a partial vacuum, as back pressure, up to 85 kPa
Vacuum system	Down to 850 mBar vacuum available
Confining frames (simple shear)	17 rigid confining aluminium frames with a height of 3 cm each (specimen with height of 51 cm and cross section 40 cm x 40 cm)
Loading frames for direct shear	Upper and lower load frames for specimen installation (each frame with height of 20 cm and cross section 40 cm x 40 cm)
Utility for submerged friction tests	Additional frame to enable submerged direct shear tests
Segment of car wheel	Fixed on the vertical piston to simulate vertical loading by the car wheel
Load control and data acquisition system	LabView based system, internally developed
Workshop	For the design and manufacturing of necessary tools, instruments etc. to be used in the test.

2.4 Sensors and instrumentation used in the facility

A wide range of sensors is available for the large-scale triaxial apparatus. Table 5 provides a short overview of the parameters that can be measured. Since the instruments are regularly updated and/or replaced please check the most recent possibilities when preparing tests. All sensors can be calibrated in-house and are traceable to (inter)national standards.
Additional sensors can be added upon request.

Table 5 Sensor and instrumentation for large-scale apparatus

Physical magnitude to be measured	Type of sensor	Description
Displacement	Displacement (LVDT) GOM Aramis	Several types, brands, ranges and accuracies of LVDTs are available for measurements in vertical and horizontal direction Local small strain measurements in range ≈ 10^{-5} Optical system (GOM Aramis) for displacement measurements

Physical magnitude to be measured	Type of sensor	Description
Pressure Pad	Soil pressure	Real-time tactile pressure measurements in range up to 200 kPa, active size 20 cm x 160 cm (total area or partly can be used), pressure mapping and analysing software available
Load	Load transducers	Two consecutive load cells are available for accurate load measurements in a vertical direction to capture the whole range from very small (up to 10 kN) to very high (up to 200 kN) loads. 200 kN load cell for the horizontal direction.
Shear wave velocity	Accelerometers	A pair of accelerometers to measure shear wave arrival time.
Pressure	Pressure sensors	Vacuum measurements, 100 kPa

2.5 Test description

2.5.1 Type of tests/Problems that can be explored

The large-scale triaxial apparatus can be used for testing geomaterials (different types of soils, waste materials, artificial granular materials, geosynthetics, etc.) and the interactions (e.g. friction characteristics) among them. Research areas normally supported by the infrastructure are geotechnics, soil mechanics and soil-structure interactions for road and railway infrastructure, dam construction and other types of earthworks, among others. The characteristics of the testing facility enable testing of geomaterials at a very small strain range with synchronized monotonic or cyclic loading in vertical and horizontal direction.

2.5.2 Material suitable for the tests

The test specimen can be prepared by various types of soil materials (from fine to coarse grained) as well as other types of geomaterials (geosynthetics, geofoams, waste and secondary marginal materials etc.).
Geosynthetic reinforced soil (GRS) and interaction between various soils and geosynthetic materials are particularly suitable for the test enabling also local strain measurements in various parts of specimen.

2.5.3 Test system limitations and constraints

- All test set-ups should be designed to perform within the parameters given in Table 4 and Table 5
- All test set-ups should be approved by ZAG staff in advance
- Tests will not be performed without ZAG staff

2.6 Examples of results

Following figures (Figure 4 to Figure 8) present various types of tests conducted by the facility.
Furthermore, some typical results are shown from Figure 9 to Figure 12.

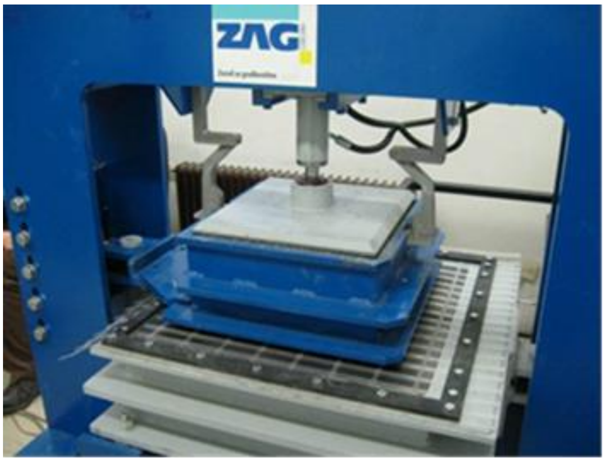


Figure 4 Loading frame when direct shear mode is used

Figure 5 Set-up for friction test between two types of submerged geomaterials

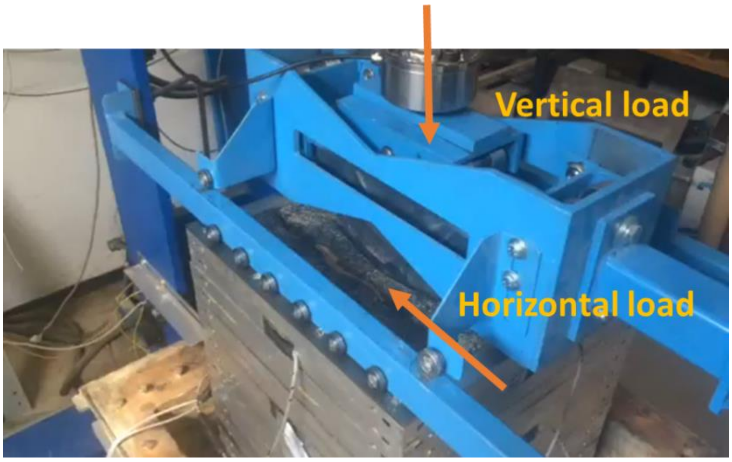


Figure 6 Pavement structure loaded by traffic load (simultaneous vertical and horizontal loading)

Figure 7 Set-up during simple shear test

Figure 8 Prismatic specimen for triaxial test. Local LVDTs attached on side.

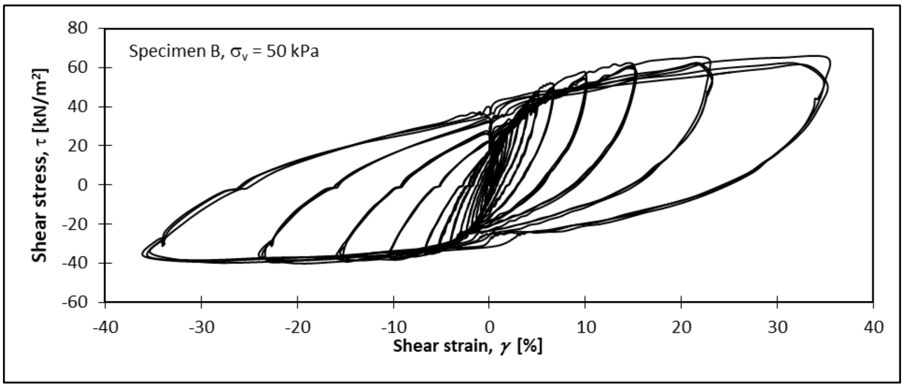


Figure 9 Results of cyclic horizontal loading

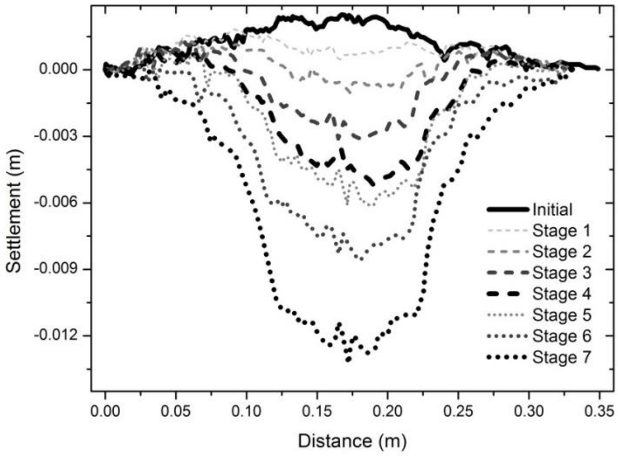


Figure 10 Rut depth measurements during various load stages of traffic load simulation test

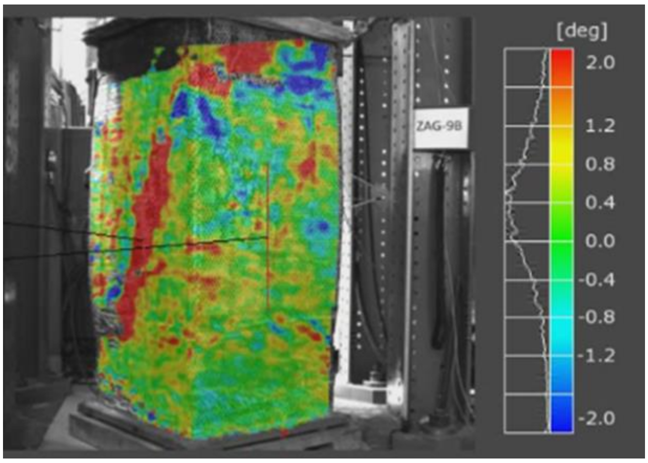


Figure 11 Displacement measurements obtained by optical system by digital image correlation technique

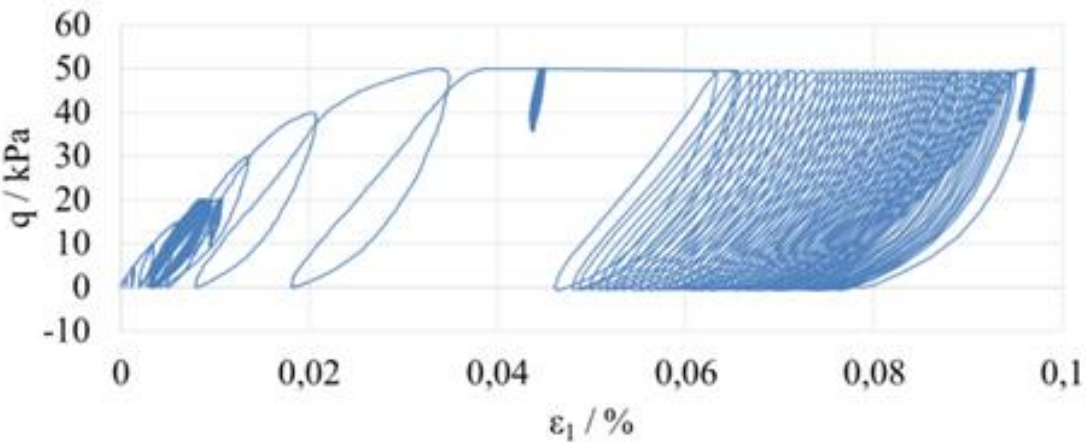


Figure 12 Typical result of vertical compression test

2.7 Reference papers

1. Lenart, S., Medved, S.P. and Žlender, B. (2017). Laboratory testing of pavement structure by traffic load simulation, Proceedings of the 19th International Conference on Soil Mechanics and Geotechnical Engineering, Seoul 2017
2. Lenart, S., Kaynia, A.M. (2019). Dynamic properties of lightweight foamed glass and their effect on railway vibration. Transportation geotechnics, vol. 21, 1-9
3. Lenart, S., Likar, B. (2019). Cyclic shear characteristics of passive house foundations consisted from XPS board placed on gravel foundation. Earthquake geotechnical engineering for protection and development of environment and constructions: Proc. of the VII ICEGE 7th International Conference on Earthquake Geotechnical Engineering (Rome, Italy, 17-20 June 2019), London: Taylor and Francus Group. cop., 3544-3551

3 TU Delft Geotechnical Centrifuge (TU Delft)

3.1 Basic information

Table 6 collects some basic information about the facility.

Table 6 Basic information of the Geotechnical centrifuge (TU Delft)

TU Delft Geotechnical Centrifuge	
Name (short)	Centrifuge
Name (long)	TU Delft Geotechnical Centrifuge
Owner	TU Delft
Location (City/Country)	Delft / the Netherlands
Address	Stevinweg 1, 2628 CN Delft, the Netherlands
Website (vernacular language)	https://www.tudelft.nl/citg/over-faculteit/afdelingen/geoscience-engineering/laboratory/facilities/geotechnical-centrifuges
Website (English)	https://www.tudelft.nl/citg/over-faculteit/afdelingen/geoscience-engineering/laboratory/facilities/geotechnical-centrifuges
Contact (e-mail)	A.Askarinejad@tudelft.nl
Head of facility (name/e-mail)	Amin Askarinejad (A.Askarinejad@tudelft.nl)
Construction year	1990

3.2 Scope of the facility

The geotechnical centrifuge at Delft University of Technology (TU Delft) is used as a physical modelling facility to investigate various geotechnical problems, such as slope stability, levees and embankments, soil-structure interaction under static and dynamic loading, tunnelling, excavations, as well shallow and deep (offshore) foundations.

3.3 Facility physical description / Technical specifications

The geotechnical centrifuge at TU Delft is beam type centrifuge with two identical baskets connected with the rotating arms. The main specifications are summarized below:

- Radius: 1.22 m
- Basket size: 400 x 500 x 500 mm
- Maximum payload: 30g at 300g
- Max rotation velocity: 450 RPM
- Max. data logging frequency: 200 kHz
- Number of data logging channels: 46
- Data transfer system: wireless router and fibre-optic slip rings

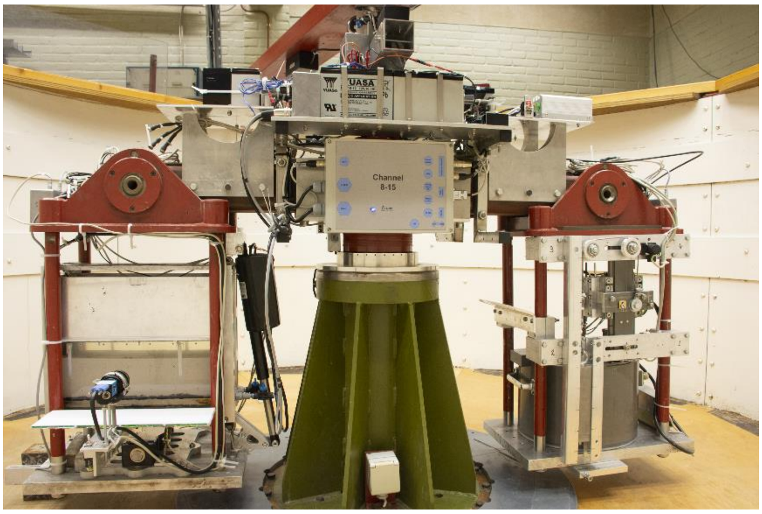


Figure 13 The geoetchnical centrifuge at TU Delft

3.3.1 Centrifuge systems/equipments/utilities

The geotechnical centrifuge at TU Delft is equipped with advanced control and monitor systems, specific actuators for different geotechnical problems and utilities for the preparation of models. Detailed descriptions of the system/equipment/utilities are provided as follows.

Data acquisition system

The geotechnical centrifuge is equipped with an advanced data acquisition system. For different applications, three data logging boxes, namely slow speed box, medium speed box and fast speed box, are developed, which can log the data at frequencies of 0.5 Hz, 250 Hz and 200 kHz, respectively. The whole data acquisition system has a total of 46 channels (16 slow speed channels, 16 medium speed channels and 14 fast speed channels). All three data logging boxes are integrated into a single acquisition system and can work simultaneously. A fully in-house developed data acquisition software is installed on the on-board computer to control the data logging boxes. The data acquisition system is compatible to the electric signals from different sensors, including (but not limited to) load cells, displacement sensors (LVDTs and potensiometers), accelerometers, total pressure sensors, pore water pressure transducers, and strain gauges.

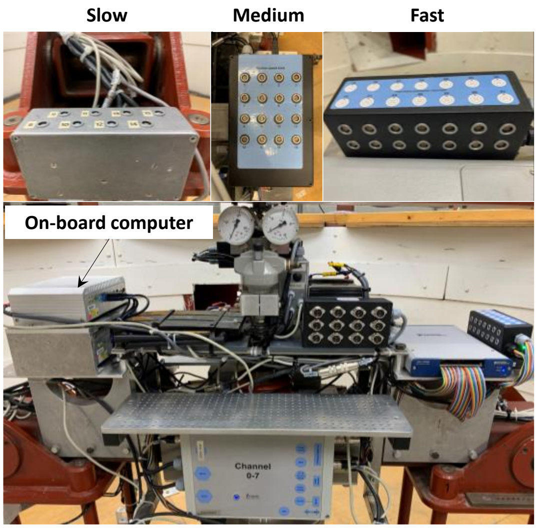


Figure 14 Data logging and control system of the centrifuge at TU Delft

Imaging and video monitoring systems

The centrifuge is equipped with a high-speed, high-resolution camera (DMK 33UP5000) and two GoPro cameras (HERO 4 and HERO 7 BLACK). The DMK camera is used to provide high-resolution images for Particle Image Velocimetry (PIV) analysis, while the GoPro cameras are used for continuous video recording with a possibility of high-speed imaging. The DMK camera has a resolution of 2592×2048 pixels with a frame rate up to 60 fps. Both cameras can operate steadily at an acceleration of 100g.

Figure 15 High-speed high-resolution camera of the centrifuge at TU Delft

Two-dimensional loading system

The centrifuge is equipped with a two-dimensional loading system, as shown in Figure 16. The loading system consists of two motors in horizontal and vertical directions, allowing to perform load/displacement-controlled monotonic/cyclic tests. The allowable moving distance in both vertical and lateral direction is larger than 100 mm. The whole system can be controlled remotely from the control room using the integrated test control system of the geotechnical centrifuge. A separate control box is also designed and mounted on the frame of backet, which can be used to control the two motors manually.

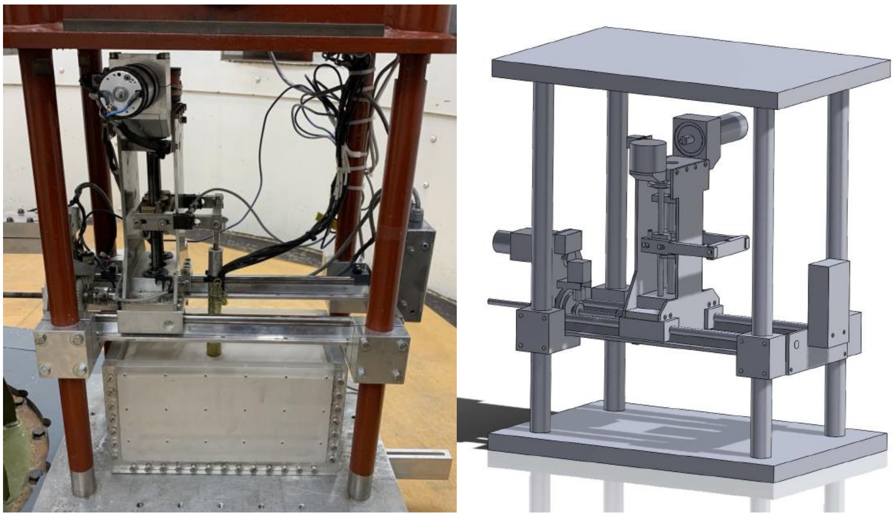


Figure 16 Two-dimensional loading system of the centrifuge at TU Delft

Submarine landslides simulating system

A single plane rotatable setup is designed for the geotechnical centrifuge to model static liquefaction of submarine slopes induced by the slope oversteepening from the scouring effect or dredging actives. The setup can also be used to study the response of buried pipeline in slope seabed. An overview of the setup is shown in Figure 17. The base plate, supporting the strongbox, is connected to the 40 mm rotating axis with five bearing blocks. The setup can rotate using a linear actuator (Linak 28210040150100, capacity: 1 kN). Six shaft blocks connect the casing of the rotating axis to the centrifuge carrier. The outer frame, which consists of four angled profiles at four corners and a lid plate on the top, keeps the strongbox in place and prevents sliding during tilting. A potentiometer (S13FLP25A) linking the base plate and the centrifuge carrier is used to measure the tilting angle. For safety reasons, in case of excessive tilting two end switches were installed. Metal components of the setup are made of (7075 aluminium sheet) and designed to be as light as possible. The weight of the sample is mainly carried by the casing of the rotating axis below the middle of the strongbox; therefore, this structure of the setup requires a low capacity for the linear motor. Furthermore, a smooth and linear change of load acting on the linear motor during tilting is expected. The setup can bear a maximum static load of 47 kN. The maximum tilting angle is 20◦. By controlling the linear motor, the strongbox can rotate with a tilting rate ranging from 0.1◦/sec to 2.0◦/sec with a precision of 0.002◦/sec.

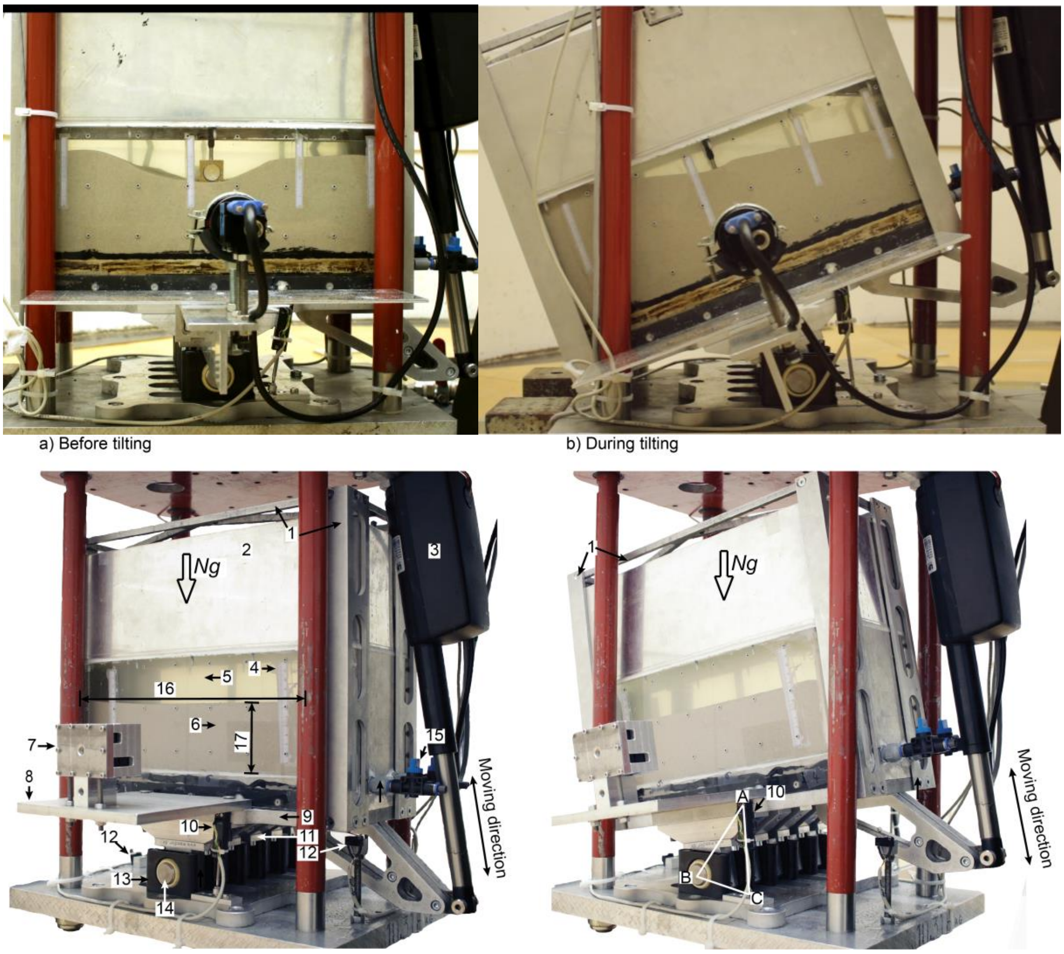


Figure 17 Submarine landslide simulating system. Test set-up in the centrifuge carrier (after Zhang and Askarinejad (2019)):

1) outer frame; 2) extension box; 3) linear motor; 4) scale; 5) fluid; 6) submerged sand; 7) high resolution, high speed camera; 8) camera holder; 9) base plate; 10) linear potentiometer; 11) bearing blocks; 12) switches; 13) shaft blocks; 14) rotation axis; 15) valves; 16) sample length: 355 mm (model scale); 17) sample height

Electro-mechanical pile driving hammer

An electro-mechanical impact pile driving hammer is developed for the centrifuge to model the pile driving problem, as shown in Figure 18. The pile driving setup consists of three main elements: the pile driving hammer, the ram mass system, and the pile-anvil system. The pile driving hammer includes the motor housing, the load frame, ram mass release mechanism and the counterweight. The hammer system is designed to replicate the IHC Hydrohammer S series hammer, which has a maximum impact speed of 6.3 m/s and a blow energy between 20 and 500 kJ. The ram mass system includes the ram mass, the ram mass guiding beam, and the guiding beam fixation. The pile system includes the pile, the pile cap, the motor-pile connection, and the pile guide. The basis of the lift mechanism is a flywheel that picks up the ram mass at its lowest point and releases it at a predefined point. From this point the ram mass accelerates under free fall. As the ram mass strikes the anvil, the pile will be driven into the soil. Following the strike on the anvil, the pile driving hammer moves down towards the pile to keep the fall height constant. The ram mass is subsequently lifted again and the process repeats.

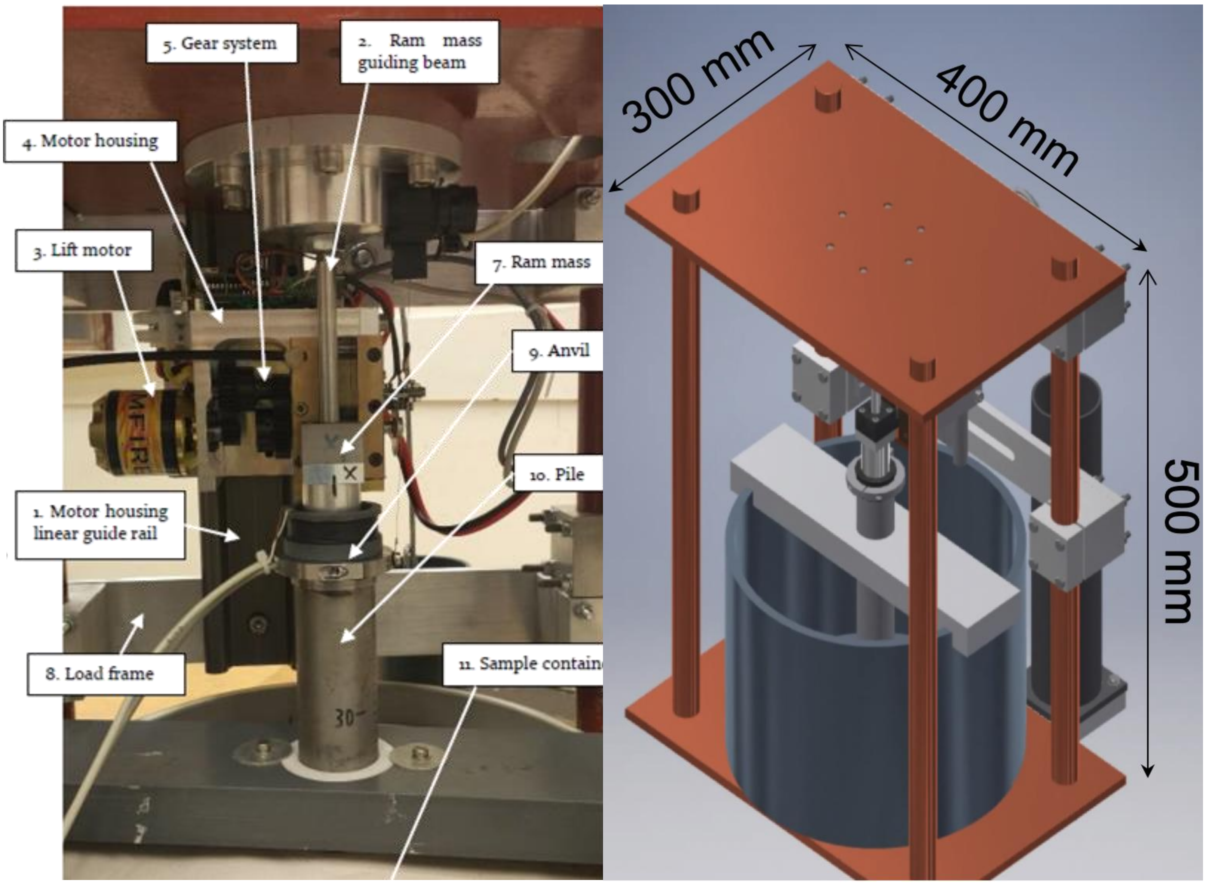


Figure 18 Pile driving hammer (Quinten 2020 and Van Zeben 2018)

Suction caisson installer

The geotechnical centrifuge is equipped with a suction caisson installer, designed to model the installation process of suction caisson anchors/foundations. Combined with the two-dimensional loading system, the setup is capable of studying the cyclic vertical/lateral response of suction caisson anchors/foundations after the installation. The test setup consists of four main parts: the strong box, the pump, the solenoid valve, and the reservoir. The reservoir is connected with the strong box through the pump and the solenoid valve, which can control the flow rate. During the test, an external gear wheel pump is used to apply necessary negative pressure or suction for installation of the suction caisson. External gear pump is a positive displacement pump composed of a casing with two meshing gears with external teeth to facilitate flow. The pump is powered by a 12 V rechargeable battery mounted on the centrifuge stem. A pneumatic solenoid valve is used to control the installation process during gravity flow. It is an electro-mechanical valve in which the solenoid (electromagnet) uses an electric current to generate magnetic field and this field exerts a force on the plunger, which is pulled towards the centre of the coil to open the orifice. It is a spring valve controlled using the control computer. Flow is achieved using the head difference between the water in strong box and the reservoir.

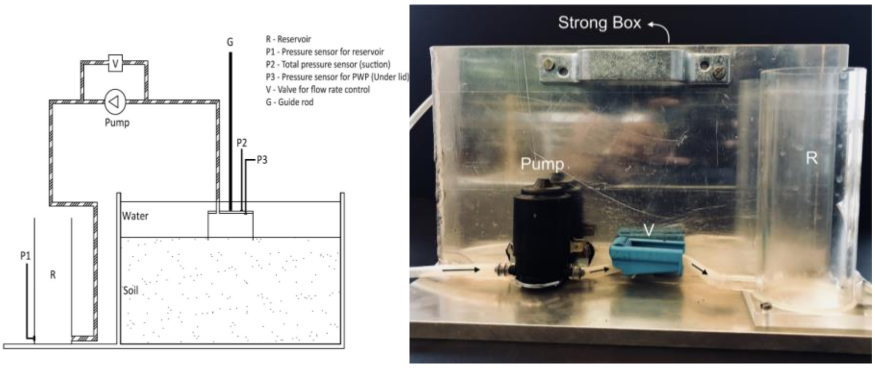


Figure 19 Suction caisson installer of the TU Delft Geotechnical Centrifuge (after Sudhakaran 2018)

Retaining wall simulator

This test setup is developed for the geotechnical centrifuge to simulate the active/passive movements of retaining walls of excavations, as shown in Figure 20. The test setup consists of three main parts: the strong box, the rigid retaining wall, and the electrical mechanical system to horizontally push the retaining wall. The strong box is made of stiff Plexiglas plates in combination with aluminium base and side parts. This strongbox is designed to be very stiff to minimize effects from bending of the walls during the centrifuge flight. A horizontal actuator is mounted on the strong box and connected with the rigid retaining wall. The setup has been proven to work up to 100g and has a maximum horizontal load capacity of 5000 N. Using the pulse wheel, the wall displacement and velocity can be monitored and controlled accurately. A calibrated load cell is installed between the actuator and the model sheet pile wall to monitor the loads acting on the retaining wall.

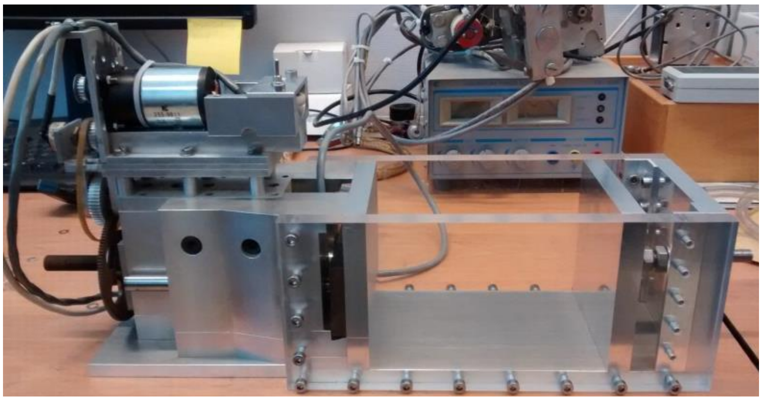
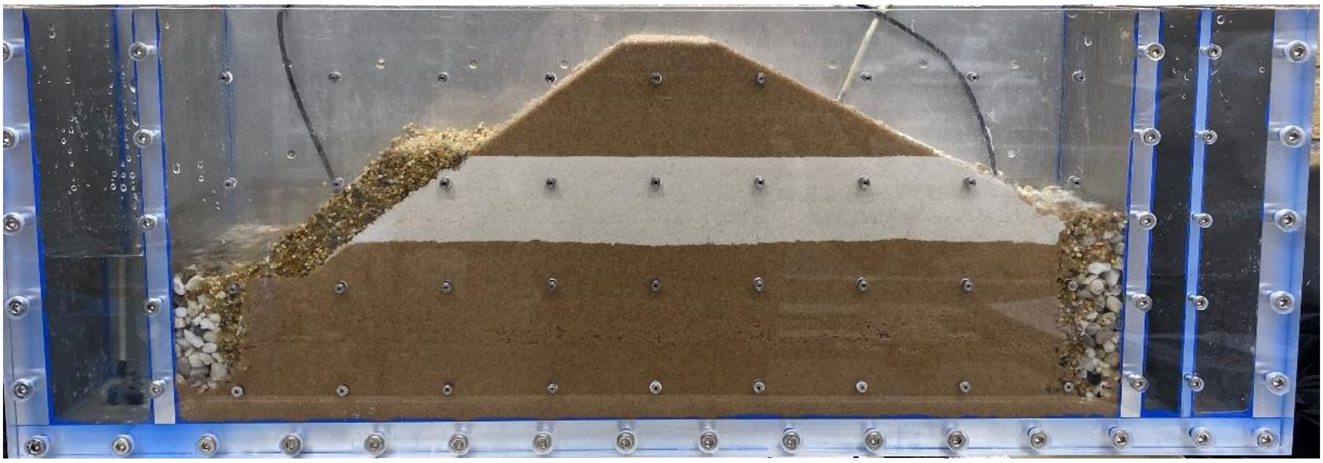


Figure 20 Retaining wall simulator of the geotechnical centrifuge at TU Delft (after Hopman 2015)

Levees flood simulator

A flood simulator is designed for the geotechnical centrifuge at TU Delft to study the seepage through and stability of levees subjected to sudden changes in the water table. The system is capable of simulating desired hydrographs. The levee can be constructed with various layers of soil, and quantities such as pore pressure, water table, and displacement field of the levee can be monitored.



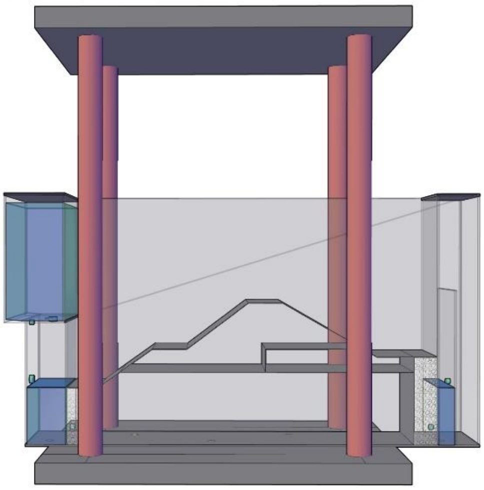


Figure 21 Levee flood simulator of the geotechnical centrifuge of TU Delft

Miniature CPT

A miniature-CPT is developed for the geotechnical centrifuge at TU Delft to characterize the test sample and provides input for the CPT based design methods of foundations. Figure 22 shows a sketch of the developed mini-CPT at TU Delft centrifuge lab. The penetrator has a diameter of 7.5 mm with a standard 60-degree cone tip. The cone tip is made of steel and connected with a steel inner rod. The inner rod has a diameter slightly smaller than the outer tube. A Teflon ring is installed between the inner rod and the outer tube, allowing to constrain the verticality of the rod without applying additional friction force. During the test, the soil pressure acting on the cone tip will be transferred to the inner tube and measured as a total force by the load cell connected with the inner tube. The load cell has a measurement range of 2.65 kN, which is equal to a tip resistance (q_c) of 60 MPa. The whole penetrator is designed in a modular mode, which allows for changing the components independently based on the requirement of the tests. The penetrator has a maximum depth of 150 mm equivalent to a depth of 15 m in protype at a centrifuge acceleration of 100g. The mini-CPT can be easily installed on the two-dimensional load actuator in the lab. A photo of the mini-CPT installed on the actuator is also presented in Figure 22.

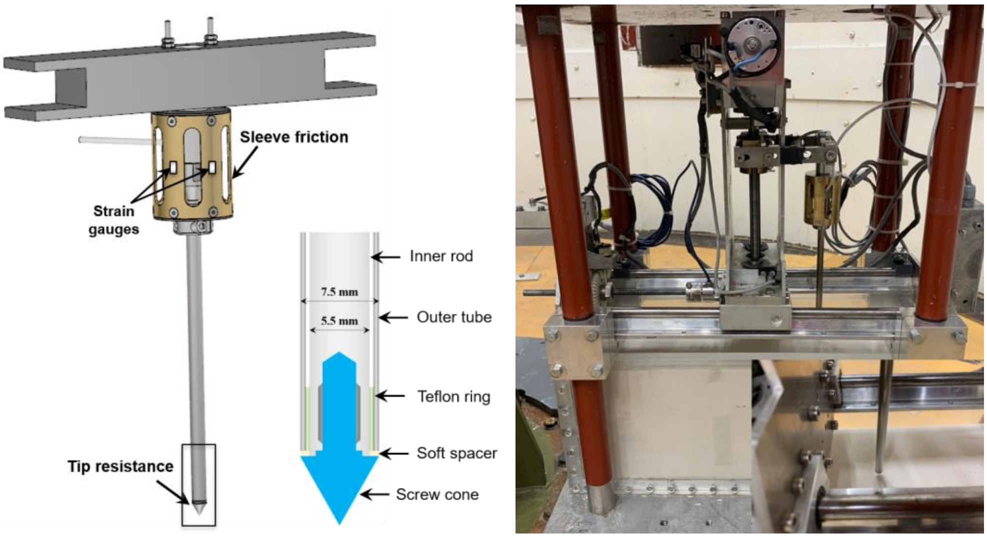


Figure 22 Miniature CPT of the geotechnical centrifuge of TU Delft (after Honarvar 2020, and De Lande et al. 2020)

Sand pluviator

For the preparation of sand sample, the sand raining machine is developed at the TU Delft centrifuge lab. As shown in the Figure 23, the sand will be stored in a triangular-prism shaped hopper first. A line-styled gap located at the bottom ridge of the sand hopper can be opened manually. The open width can be adjusted by a spiral calliper. By screwing the spiral calliper, the gap width can be adjusted to produce different thicknesses of the “sand curtain”. This allows to control the sand grains’ raining intensity and generate different relative density seabed. Meanwhile, the height of sand hopper can also be adjusted by driving two vertical servo motor belts. By changing the opening, the height and the speed, sand sample with a wide range of density can be prepared. During the sample preparation process, the sand falling outside the box will be transported to a cubic sand container by a servo motor belt. Sand grains accumulating in the cubic recycle container can be transported upwards to refill the sand hopper, by an electric vacuum pump. The whole sample preparation process can be performed automatically.

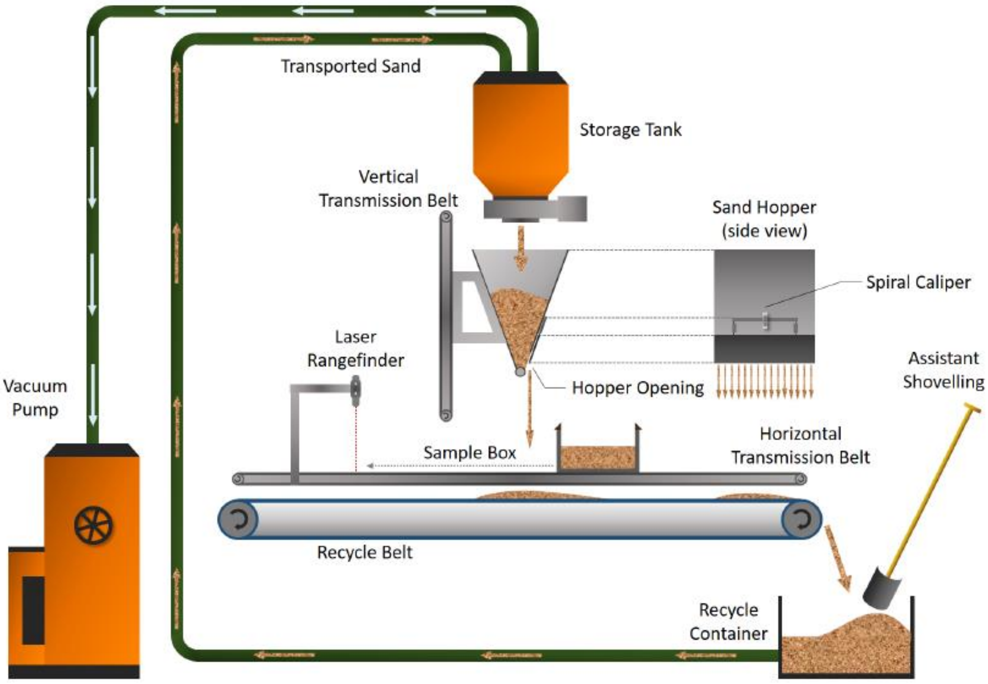


Figure 23 Sand pluviator of the geotechnical centrifuge of TU Delft

Vacuum chamber system

A vacuum chamber system is developed at the TU Delft centrifuge lab. The vacuum bucket is EUROVACUUM-419200 and has a volume of 70 litre with a transparent lid and a pressure reader, allowing to monitor the sample/sensor and pressure inside. The VE-2100 type vacuum pump is used to remove the air inside the vacuum bucket. The setup is designed to create a de-aired environment for the sandy sample saturation and saturation of the pore water pressure transducers.

Figure 24 Vacuum chamber of the geotechnical centrifuge of TU Delft

Clay consolidation set-up

The setup has a rigid reaction frame and a platform;the platform can move vertically at designed speed to load or unload the clay sample. Additional displacement sensor and load cells are connected with an independent data logging system. The surcharge on the clay sample surface (i.e. the consolidation pressure) and the degree of consolidation of the sample can be calculated based on the reading of load cell and displacement.

Figure 25 Clay consolidation system of the geotechnical centrifuge of TU Delft

3.4 Sensors and instrumentation used in the facility

Table 7 Sensor and instrumentation for Geotechnical centrifuge of TU Delft

Physical magnitude to be measured	Type of sensor	Description	Range measurement	Accuracy
Displacement	Potentiometer	LCP8S-10	10 mm	2% FS
	Laser displacement sensor	FDRF602-20/10-232-U-IN-AL-3	10 mm	0.05% FS
	Laser displacement sensor	FDRF602-20/25-232-U-IN-AL-3	25 mm	0.05% FS
Pore pressure	Pore pressure transducer	MEAS France EPB-PW-1BS/Z0/PC0.5/L5M	0-100 kPa	1%FS
	Pore pressure transducer	MEAS France EPB-PW-1.5BS/Z0/PC0.5/L5M	0-150 kPa	1%FS
	Pore pressure transducer	GEOTOP-DSPII-700 kPa	0-700 kPa	0.1%FS
	Pore pressure transducer	MPXH6400A	20-400 kPa	1.5%FS
	Optical pressure sensor			
Soil Pressure	Soil pressure	KYOWA PS-0.5KC	50 kPa	1%FS

Physical magnitude to be measured	Type of sensor	Description	Range measurement	Accuracy
	Soil pressure	KYOWA PS-1.0KC	100 kPa	1%FS
	Soil pressure	KYOWA PS-2.0KC	200 kPa	1%FS
	Soil pressure	KYOWA PS-5.0KC	500 kPa	1%FS
	Soil pressure	TML PDA-50KPB	50 kPa	1%FS
	Soil pressure	TML PDA-100KPB	100 kPa	1%FS
	Soil pressure	TML PDA-200KPB	200 kPa	1%FS
	Soil pressure	TML PDA-500KPB	500 kPa	1%FS
	Soil pressure	Flexiforce A101	44 N	4.5%FS
Force	Force transducers	BRUSTER, 8431 EN	5 kN	0.2%FS
	Force transducers	HTC-SENSORS, TAL220	100 N	0.05%FS
Strain	Strain gauge	TML FLA-03-23-1LE	5000 με	1 με
Video camera	High-resolution industry camera	DMK 33UP5000	2592×2048 (5.3 MP)@60 fps	
	GoPro	HERO 7 BLACK		

3.5 Test description

3.5.1 Type of tests/Problems that can be explored

The main principle of geotechnical centrifuge is to generate the same stress condition of a full-scale problem in a scaled model by creating an enhanced gravitational field. In addition, due to the high gravitational acceleration and the reduced geometric dimension of the model, the seepage and consolidation processes lasting decades in the prototype can be scaled to hours in the geotechnical centrifuge.

Various problems can be explored using the geotechnical centrifuge include (but are not limited to):

1. Offshore geotechnical engineering: behaviour of foundations and anchors (e.g. gravity based foundations, monopiles, suction caissons, spudcan, suction anchors, plate anchor, etc.) for various offshore structures (e.g. wind turbines, oil-gas platforms, jack-ups); stability of submarine slope and landslides, pipeline stability.
2. Levees and embankments: construction and in-service performance of embankments
3. Tunnelling and excavations: stability of the tunnel face and the excavation and its influence of the ground infrastructures; behaviour of tunnel lining; design of the retaining wall/support systems.
4. Unsaturated soil mechanics: soil vegetation interaction; influence of vegetation on slope stability.
5. Soil structure interaction: shallow and deep foundations of urban structures under (combined) vertical/lateral static and dynamic loading.

3.5.2 Material suitable for the tests

The geotechnical centrifuge at TU Delft is designed for the geotechnical problems in both sandy and fine-grained soils. As explained in the preceding section, the centrifuge lab at TU Delft is equipped with different utilities for the preparation of different type of soils (both sand and clay). For the preparation of sandy soil, the sand pluviator and the vacuum chamber can be used. The sand pluviator can uniformly produce a dry sand sample with the relative density between 40% and 80%, while the vacuum chamber can be used for preparing the sandy samples saturated with water and viscous fluid. For the clay samples, a clay slurry mixer and a consolidation system are available in the lab. By using the consolidation system and the centrifuge, the clay sample with different OCR or shear strength profiles can be achieved. Combing the setups for sand and clay samples, homogeneous sand seabed, homogeneous clay seabed or layered seabed with sand and clay can be prepared.

3.5.3 Test system limitations and constraints

- The dimension of the model is limited by the available space of centrifuge platform;
- The weight of test model is limited by the carrying capacity of centrifuge;

3.6 Example of result/Relevant projects performed in the facility

The geotechnical centrifuge at TU Delft has a history of more than thirty years and have been used in different types of projects related to the foundation engineering, slope stability, tunnelling, and excavations.

3.7 Reference papers

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2- Zhang, W., and Askarinejad, A. 2019. Centrifuge modelling of submarine landslides due to static liquefaction. Landslides doi: 10.1007/s10346-019-01200-z.

3- ASKARINEJAD, A., WANG, H., CHORTIS, G. & GAVIN, K. 2020. Quantifying the beneficial contribution of scour protection layers on the lateral response of monopile in dense sand. Géotechnique Letters, under review.

4- CHORTIS, G., ASKARINEJAD, A., PRENDERGAST, L., LI, Q. & GAVIN, K. 2020. Influence of scour depth and type on p–y curves for monopiles in sand under monotonic lateral loading in a geotechnical centrifuge. Ocean Engineering, https://doi.org/10.1016/j.oceaneng.2019.106838.

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6- LI, Q., PRENDERGAST, L., ASKARINEJAD, A., CHORTIS, G. & GAVIN, K. 2020. Centrifuge Modelling of the Impact of Local and Global Scour Erosion on the Monotonic Lateral Response of a Monopile in Sand. Geotechnical Testing Journal, 43, 5.

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8- ZHANG, M. W. & ASKARINEJAD, D. A. 2020. Centrifuge modelling of static liquefaction in submarine slopes: the scaling law dilemma. Canadian Geotechnical Journal, DOI: 10.1139/cgj-2019-0417.

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10- ASKARINEJAD, A., QUINTEN, T. O., GRIMA, M. A., VAN'T HOF, C. & GAVIN, K. 2020. Use of optical fibres to measure pore water pressure development during impact pile diving: a geotechnical centrifuge study. In: LAUE, J. & BANSAL, L. (eds.) European Conference of Physical Modelling in Geotechnics (ECPMG 2020). Lulea, Sweden.

11- DE LANGE, D., HONARDAR, S. & ASKARINEJAD, A. 2020. Design of a Miniature Cone Penetrometer for the Geotechnical Centrifuge of Delft University of Technology. In: LAUE, J. & BANSAL, L. (eds.) European Conference of Physical Modelling in Geotechnics.

12- ZHANG, Y., SUDHAKARAN, K. & ASKARINEJAD, A. 2020. Centrifuge Modelling of Suction Caissons Subjected to Cyclic Loading in Tension. In: LAUE, J. & BANSAL, L. (eds.) European Conference of Physical Modelling in Geotechnics. Lulea, Sweden.

3.8 Other relevant information

Possible bullets to be included in this section:

- Amount of material needed: 10 to 15 kg/model
- Test duration: 10 minutes to max. 1 day
- Type of format result delivers to the client (only data/interpretation) (worksheet…): *.csv
- Connection with other TA providers: The submarine landslide simulator is a scaled model of the liquefaction tank at TU Delft

4 Beam and Drum Centrifuge (ETHZ)

4.1 Basic information

Table 8 presents the two main geotechnical centrifuge facilities, accommodated in the Geotechnical Centrifuge Center (GCC) in ETHZ.

Table 8 Basic information of the facilities in the Geotechnical Centrifuge Center (GCC) in ETHZ

(a) Beam Centrifuge	
Name (short)	Beam Centrifuge in ETHZ
Owner	ETHZ
Location (City/Country)	Zurich/Switzerland
Address	Stefano-Franscini Platz 5, 8093 Switzerland
Website	https://geotechnics.ethz.ch/geotechnical-centrifuge-center/beam-centrifuge.html
Contact (e-mail)	Eva Korre: eva.korre@igt.baug.ethz.ch Alex Marin: alexandru.marin@igt.baug.ethz.ch
Head of facility (name/e-mail)	Ioannis Anastasopoulos ioannis.anastasopoulos@igt.baug.ethz.chmailto:
Construction year	2021

(b) Drum Centrifuge	
Name (short)	Drum Centrifuge in ETHZ
Owner	ETHZ
Location (City/Country)	Zurich/Switzerland
Address	Stefano-Franscini Platz 5, 8093 Switzerland
Website	https://geotechnics.ethz.ch/geotechnical-centrifuge-center/drum-centrifuge.html
Contact (e-mail)	Eva Korre: eva.korre@igt.baug.ethz.ch Alex Marin: alexandru.marin@igt.baug.ethz.ch
Head of facility (name/e-mail)	Ioannis Anastasopoulos ioannis.anastasopoulos@igt.baug.ethz.chmailto:
Construction year	1999

4.2 Scope of the facility

The Geotechnical Centrifuge Center (GCC) encompasses two geotechnical centrifuges, a 9 m diameter (500gton capacity) beam centrifuge and a 2.2 m diameter (440gton capacity) drum centrifuge, a cutting-edge earthquake simulator, a Miniaturized Tidal Generator (MTG), and a variety of actuators, tool platforms, and highly specialized devices and sensors. Our experimental infrastructure is predominantly used for research and teaching purposes. On demand, we also offer highly-specialized consulting services to the industry.

4.3 Facility physical description / Technical specifications

4.3.1 KRUPP centrifuge

The beam centrifuge consists of an arm supporting two swings, in which the model and the counterweight are placed. It is connected to the chamber with a bottom and a top bearing, ensuring higher stability of operation. The centrifuge is not brand new, but rather an example of how existing equipment can be reused for research. The centrifuge was constructed by KRUPP and was originally installed in RUHR University Bochum, were it was under operation for over 20 years. Decommissioned in Germany, it was acquired by ETHZ and has been fully refurbished in terms of hydraulics, electronics, and control systems.

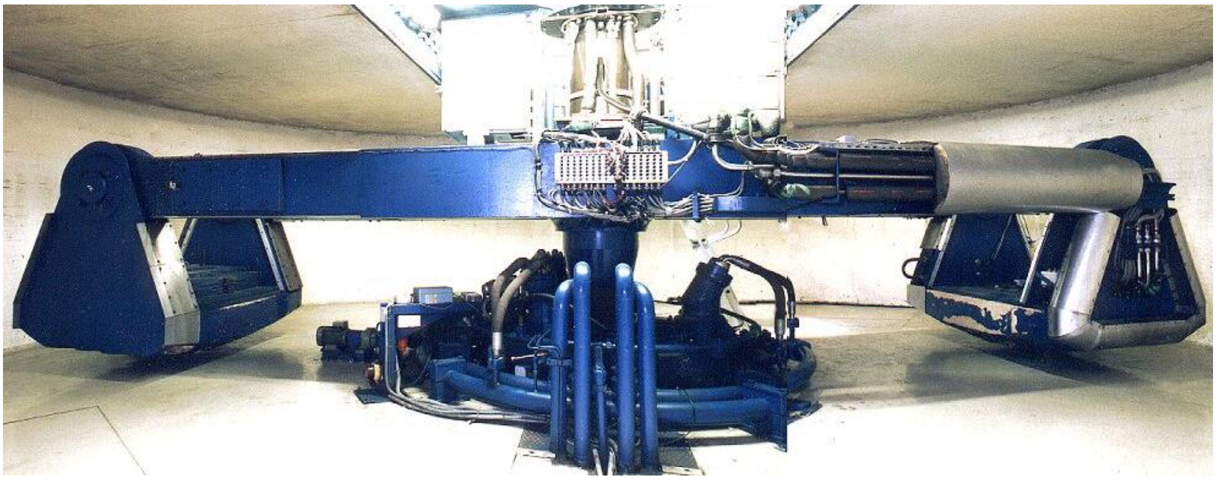


Figure 26 The 9 m diameter 500 gton capacity KRUPP geotechnical beam centrifuge (photo from Bochum).

With an effective diameter of 8.25 m, the centrifuge can be accelerated up to 250g carrying a payload of 2 tons (or equivalently 5tons at 100g). Its 500gton capacity is the largest in Europe and one of the biggest in the world. Each swing has a platform of 1.25 x 1.25 m, where the soil container is placed. The setup offers the possibility of a soil container of up to 2 m length (extending 0.375 m from the platform on each side), allowing testing large models corresponding to up to 500 m length (at the maximum g level).

4.3.1 Earthquake Simulator

Custom-designed for the KRUPP centrifuge, the Actidyn BC-5810 earthquake simulator is capable of delivering horizontal seismic ground motions of any target waveform (including recorded and artificial motions) 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. This new earthquake simulator is specially-designed offering the possibility to install a soil container of up to 2 m length (extending 0.375 m from the platform on each side), which can be crucial for testing structure-soil-structure interaction between neighboring structures.

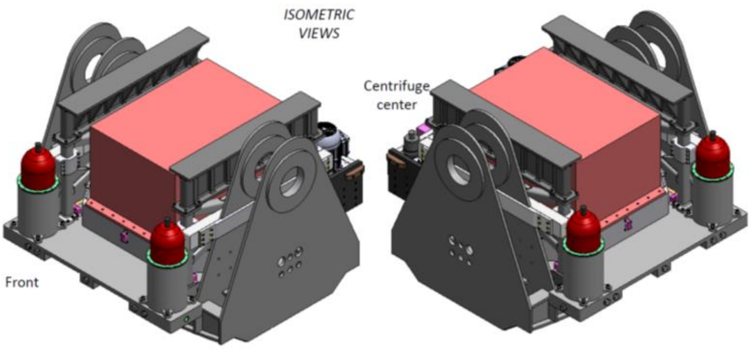


Figure 27 Schematic of the Actidyn on-board earthquake simulator.

4.3.1 Miniature Tidal Generator

A new experimental apparatus has been developed, aiming to minimize size, weight, and complexity of the Tidal Generator concept, rendering the apparatus adaptable for centrifuge modelling. The key innovation of the developed “Miniaturised Tsunami Generator” – MTG (Jones & Anastasopoulos, 2020) is the ability to recirculate water around the model space. The water that inundates and then passes beyond the model space is recirculated back into the reservoir and reused, maintaining the water flow that is necessary to achieve the desired large wavelength. By recycling water that has inundated and then flowed out of the model space, we can drastically reduce the length of the channel, only producing a small portion of the target wave form at any time. This allows a drastic reduction of the dimensions of the apparatus and of the water reservoir that is required to produce the wave.

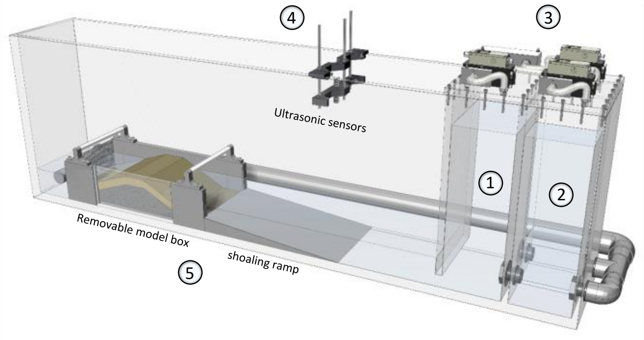


Figure 28 A primary tidal tank

(1), secondary pump tanks (2), proportional valves (3) and a vacuum pump produce the target waveform. Water surface profiles are monitored with ultrasonic sensors (4). The flume can accommodate a model box and shoaling ramp (5).

To allow centrifuge adaptation, the MTG is designed to be as compact as possible, having a total length of 2 m, a breadth of 0.3 m and a height of 0.5 m. The flume is 1.8 m in length and the initial water depth at the model space is minimum 5 cm. At a 1:100 (N = 100) scale, this corresponds to a prototype of 180 m length and 5 m minimum depth. Geotechnical models are constructed outside the apparatus, in a model box of 0.5 m length and 0.2 m height (50 m x 20 m at prototype scale), which is then installed into the flume. The removable model box allows pluviation using the same sand raining system used for centrifuge testing. The model box is equipped with porous end plates of variable height, which allow for water infiltration and transmission of pore pressures through the longitudinal boundaries. A Perspex window is installed along the sidewall of the model box to allow capturing digital images of the model to be subsequently used for calculation of soil displacements and deformations employing PIV.

The MTG can be used to model scouring around bridge piers, which is one of the main causes of bridge failure. A novel hybrid approach has been developed to study the mechanical behaviour of a bridge foundation subjected to flood-induced scour. A 2-step methodology is employed, decoupling the *hydraulic* (i.e., the scour process around the bridge pier) and the *mechanical* part of the problem. The first step simulates the *hydraulic* process in 1*g* using the MTG. The morphology of the scour hole is acquired through a 3D scanner, and the inverse of the scour hole surface is 3D printed to produce a mould of the scour hole. The 3D-printed mould is used to reproduce the scour hole in a centrifuge model, which is subsequently tested under *Ng*. The second step addresses the mechanical part of the problem, using 1:*N* scaled models tested at *Ng*, thus achieving correct scaling of the in-situ stresses.

The direct (fully coupled) physical modelling of both the *hydraulic* and the *mechanical* part of the problem in a geotechnical centrifuge would be the best option to simulate the entire process as realistically as possible, provided that a proper scaling of the water flow characteristics is achieved. This will be possible with the centrifuge-mounted MTG (C–MTG), which is currently under development.

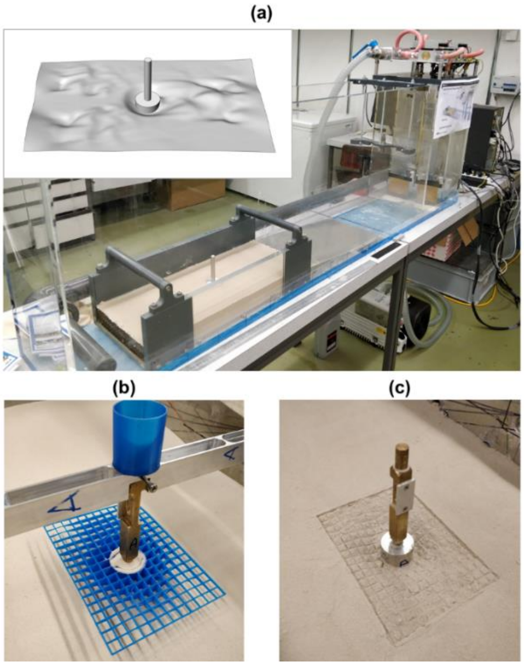


Figure 29 Hybrid decoupled methodology:

(a) development of the scour hole using the MTG and 3D scan of the scour hole surface; (b) 3D printed mould of the scour hole; and (c) reproduction of the geometry to prepare models suitable for geotechnical centrifuge.

4.3.1 Model Containers

A deformable soil container is necessary to allow realistic boundary conditions during seismic shaking. The developed laminar container has internal dimensions of 1 x 0.4 x 0.4 m (length x width x height), allowing large models to be tested at up to 100g centrifugal acceleration (100 m length in prototype scale). It consists of 20 laminate rings of 20 mm thickness, stacked together through low friction industrial sliders. The laminate rings are free to slide relative to each other (the measured friction coefficient is below 0.01), allowing the contained soil to deform as naturally as possible during seismic shaking. To minimize lateral deformations of the aluminium laminate rings due to the developing earth pressures at 100 g, two lateral supports are added in the longitudinal direction (1 m length). The lateral supports are connected with transverse stiffeners to further increase the lateral stiffness, but also to allow mounting of instruments and sensors. In the direction of loading, stoppers are installed to intercept the rings in case of excessive deformation.

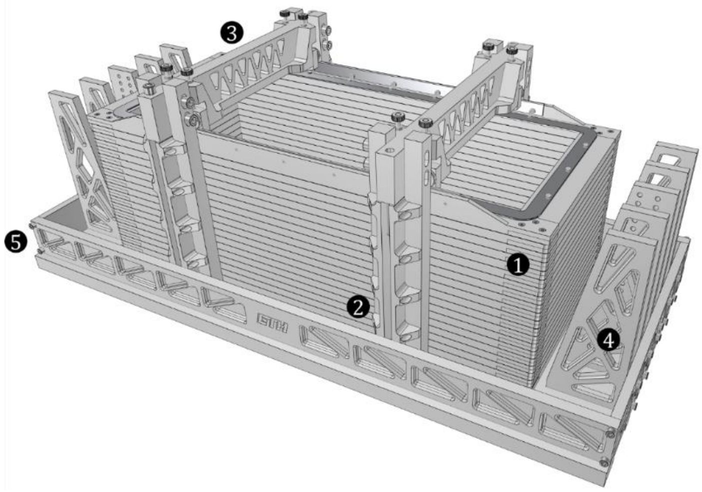


Figure 30 Schematic of the laminar container:

(1) stack of 20 laminate rings; (2) lateral support; (3) transverse stiffeners; (4) stoppers (in case of excessive deformation); and (5) reinforced baseplate.

The laboratory is equipped with a variety of strong boxes, which are typically used for static monotonic and cyclic loading tests. Most of the strong boxes have a length of 1.25 m (equal to the size of the platform), with their width and height varying from 0.6 m to 1.2 m. Some of these rectangular boxes are equipped with transparent Perspex windows to allow capturing images of the deformed model during the test, which are subsequently processed to compute displacements and stains through PIV. A trap-door container is also available, as well as a cylindrical strong box of 1 m diameter and 0.75 m height (which corresponds to a soil deposit of 75 m depth at 100g).

4.3.2 Drum centrifuge

The channel of the drum centrifuge can be accelerated up to 440g carrying a payload of up to 2 tons. A key advantage of the drum centrifuge is that the entire channel can be filled with soil, creating a model deposit of 5 m length, which corresponds to a prototype of 2 km length, over 100 m depth and 300 m width. Smaller models can be tested using strongboxes, prepared outside, and placed on the channel.
The rotation of the channel and the tool platform is provided by an external and an internal shaft, respectively. The tool platform can spin together with the channel, or independently. This allows stopping the tool platform during a test, allowing changes or adjustments of actuators and sensors mounted on the platform without stopping the test. In such a case, a shield is lowered to protect the stationary platform from the spinning channel. Communication between the on-board computer and the control room is provided by sets of electrical slip rings. An additional slip ring is mounted on the tool platform over the internal shaft, allowing supply of water to the spinning model from an external source.

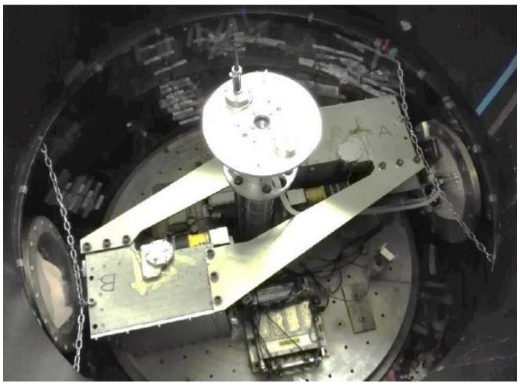


Figure 31 The geotechnical drum centrifuge with two cylindrical strongboxes installed.

Besides the data acquisition system and the on-board computer, the tool platform is equipped with vertical and horizontal servo-electric actuators. In combination with the ability of the platform to rotate independently from the drum channel, the system allows actuation in 3 degrees of freedom (vertical, horizontal, and lateral). The actuators are equipped with load cells and laser displacement transducers to control and measure the results of the test. Depending on the specific needs of the test, different tool platforms are available, containing other types of actuators and instruments.

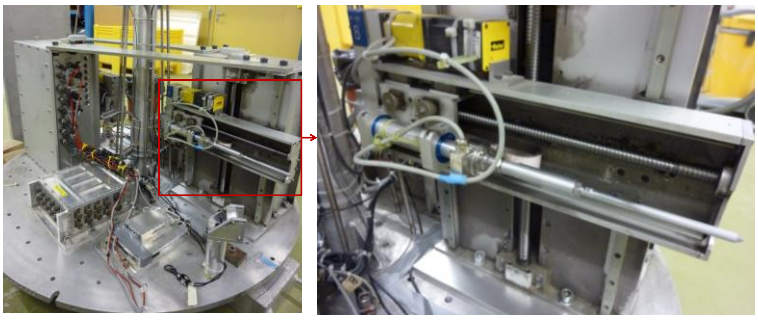


Figure 32 Tool platform (left) and zoomed-in detail of one of the actuators.

4.3.1 Combined (VHM) Loading Apparatus

A combined VHM loading apparatus has recently been developed in-house. The system has three fully de-coupled degrees of freedom (vertical, lateral translation, and rotation) and is capable of performing all types of displacement-controlled tests (e.g., swipe tests, radial displacement tests). The loading apparatus consists of 3 independent actuators, one attached to the tool platform and 2 attached to the strong box, capable of applying displacement at a controlled rate. A load cells and a laser sensor are attached to each actuator to measure the loads and control the imposed displacement.

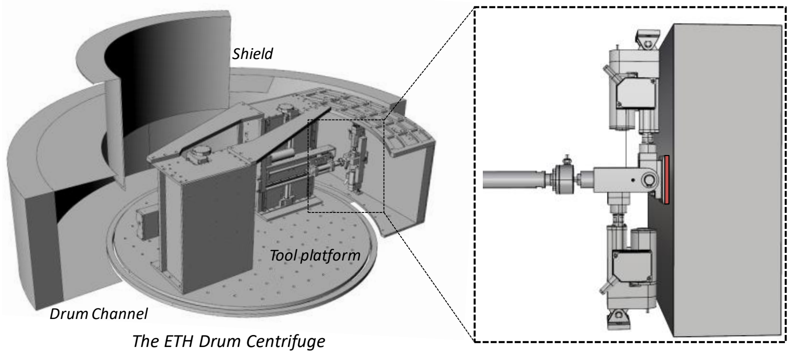


Figure 33 Schematic representation of the drum centrifuge with the VHM loading apparatus.

4.3.2 Climate Chamber

The climate chamber allows experimental simulation of rainfall-induced landslides (Askarinejad, 2013). It is equipped with a custom-built rainfall simulator, capable of imposing controlled intensity and duration precipitation. The rainfall is applied by non-uniformly distributed nozzles, extended below the strong box roof to a certain height above the slope surface to reduce the Coriolis Effect. The occurrence of overland flow (runoff) is dependent on the difference between the hydraulic conductivity of the soil and rain intensity.

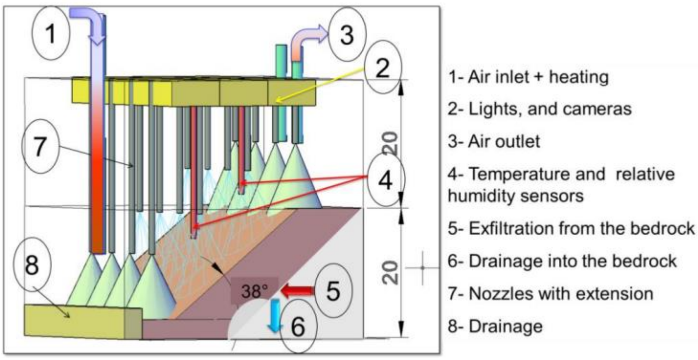


Figure 34 Climate chamber and rain simulator with dimensions in cm (Askarinejad, 2013).

Evaporation is controlled by means of air flow and increase in the ambient temperature in the drying phase of the tests. The air flow is provided by two air valves, one installed in the direction of the centrifugal rotation and one in the opposite direction. The pipe connected to the inlet valve is wrapped in a high resistance wire coil to heat the air. The relative humidity and temperature are measured at two points over the slope. Together with the suction build-up in the soil, they provide the necessary information to control the evaporation process. The water supply of the rain simulator is composed of a central water tank (CWT), magnetic valves, pipes and water channels grooved into the chamber. The water height in the CWT is monitored by a pressure difference sensor (PDS-Keller PD11). The water flow from the CWT is controlled by two magnetic water valves. High pressure pipes convey the water from the tool platform to the climate chambers, which are installed diametrically opposite to each other.

4.3.3 Water Level Control System

Initially developed to study the response of river dykes to transient water-level conditions, the water level control (WLC) system allows in-flight simulation of transient cycles of increasing and decreasing water level (Morales Peñuela, 2013). It encompasses a two-chamber 1.22 lt water tank, with a maximum discharge rate of 500 ml/s. The externally supplied water flows continuously through a pipe into the first chamber of the tank. When the water level in the first chamber reaches the height of the separation wall, it overflows into the second chamber, thus allowing drainage of the system. In this way, a fixed water level can be maintained in the water tank. The outlet of the first chamber is connected to the upper drainage line of the strongbox by a 10 mm diameter plastic hose. By connecting the water tank to the strongbox, the level of water equalises on both sides. The tank is connected to an actuator, mounted on the tool platform. Using the actuator, the water tank can be moved in the radial direction, thus allowing control of the water level during the test. Pore pressure transducers are used to control and monitor the process.

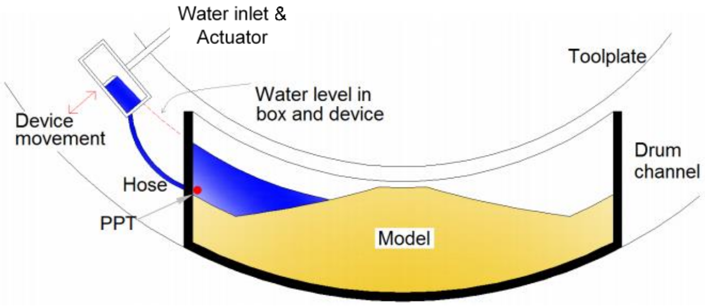


Figure 35 Schematic of the water level control system (Morales Peñuela, 2013).

4.3.4 Miniature CPTu Probe

The miniature CPTu probe (piezocone) allows in-flight measurement of soil strength, on the basis of cone resistance and side friction. As with its real-scale equivalent, when the cone penetrometer is pushed into the soil, it leads to bearing capacity failure of the soil and full flow around the cone and shaft. The penetration shaft has an outer diameter of 11.3 mm, the length of the sleeve is 36.9 mm, and the cone angle is 60°. Cone resistance and side friction are measured with built-in load cells, and a PPT (installed behind the cone tip) is used to measure the in-situ pore water pressure through an annular ceramic filter. The CPTu tool is mounted on the actuator of the tool platform, allowing the control of penetration rate and depth. The CPTu test is displacement-controlled, with a penetration rate of 0.2–2 mm/s (which corresponds to 10–100 mm/s in prototype scale).

4.3.5 Model Containers

A variety of model containers are available (always in pairs), including cylindrical and rectangular ones. The most widely used are the cylindrical containers, which have an internal diameter of 40 cm and are of 20 cm depth (allowing 20 m depth of prototype at 100g). The rectangular (square) strongboxes are of 40 cm length and 20 cm, being also equipped with a Perspex window to allow capturing images of the deformed soil-structure model, which are subsequently used to compute deformation and strains with particle image velocimetry (PIV). These rectangular boxes can be used in combination with the climate chamber to model rainfall-induced landslides (Askarinejad, 2013). Larger semi-circular strongboxes are also available, allowing larger models to be tested. With a length of 105 cm, 54 cm width, and 35 cm height, the semi-circular boxes were originally developed to model river dykes under transient water level conditions (Morales Peñuela, 2013). More recently, they were used for monotonic and cyclic loading of embedded foundations (Taeseri et al., 2019).

4.4 Sensors and Instrumentation used in the facility

The Geotechnical Centrifuge Centre (GCC) is equipped with a multitude of sensors, including high speed and high -resolution cameras, accelerometers, displacement sensors, pore-pressure transducers, time-domain reflectometers, load cells, strain-gauges, and tactile pressure sensors.

Table 9 Sensor and instrumentation for GeoModel container

Physical magnitude to be measured	Type of sensor	Description
Displacement	LVDT, Laser, High-Speed Camera	Variety of high-accuracy and different ranges LVDT and laser sensors, as well as high-speed and high-resolution cameras
Acceleration	Piezoelectric and MEMS	A variety of high-accuracy accelerometers, e. g. the Brüel & Kjaer
Pore Pressure	Pore Pressure Transducer	e. g. Druck PDCR-81
Contact Pressure	Tactile Pressure Sensor	Several sizes and ranges of Tekscan sensors
Force	Load Cells	A range of load cells (of varying capacities) used for static and dynamic loads, e. g. HBM load cell
Strains	Strain gauges	-

4.5 Test Description

With climate change leading to extreme weather patterns, record-breaking flooding is becoming the new normal. Recent such extreme events have led to the collapse of several bridges due to foundation scouring (e.g., Kalampaka, 2016). We have developed a 2-step experimental methodology to study the hydraulic and the mechanical part of the problem. In the first step, the hydraulic problem of local scour around a bridge pier is experimentally modelled in 1 g, using the recently developed MTG (Jones & Anastasopoulos, 2020).
The experimentally generated scour hole is then 3D-scanned to produce a 3D-printed mould. The latter is used in the second step to reproduce the scour hole in an N g model, subsequently tested in our drum centrifuge to study the mechanical part of the problem under proper stress scaling. Employing this hybrid technique, we have investigated foundation performance prior and after local scour through vertical, lateral monotonic, and slow-cyclic pushover tests. Our work has quantified the effect of local scour on vertical and lateral bearing capacity, questioning the common simplification of ignoring the geometry of the scour hole, making no distinction between local and general scour.

4.6 Examples of Results

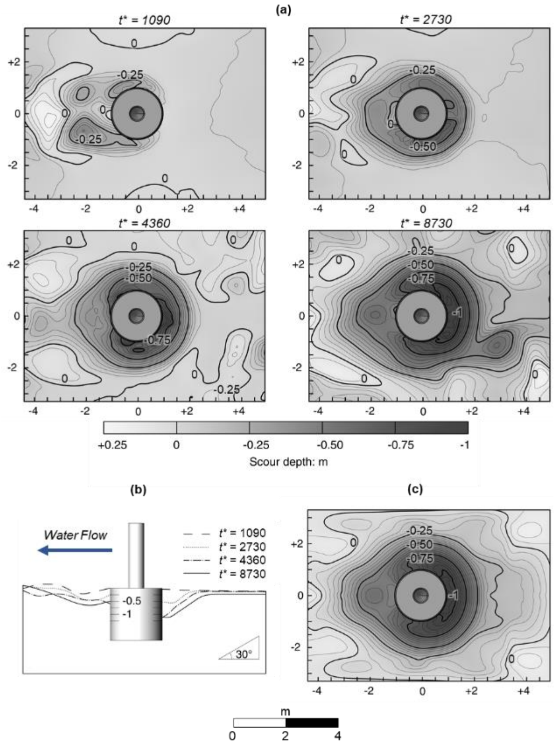


Figure 36 Time evolution of the scour hole:
(a) contour plots of bed elevation; (b) cross section at the foundation centreline; and (c) contour plot of the regularized surface used for the 3D printed mould.

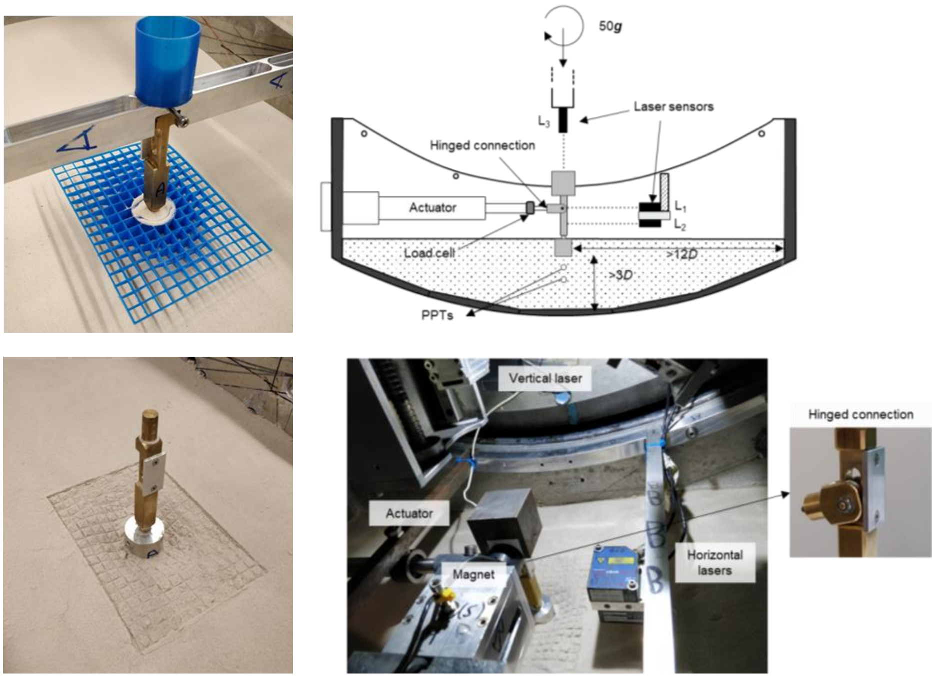


Figure 37 A mould is 3D-printed based on 3D-scanned surface of the scour hole, and used to reproduce its geometry in the centrifuge model (left); experimental setup for lateral loading in the drum centrifuge (right).

4.7 Relevant projects performed in the facility

Table 10 Summary of relevant projects performed in the Drum Centrifuge in ETHZ.

Brief description	Relevant publication(s)
Triggering Rapid Mass Movements (TRAMM) (*)	(Askarinejad & Springman, 2014), (Askarinejad et al., 2012)
Advanced Process UNderstanding and prediction of hydrological extremes and Complex Hazards (APUNCH) (*)	(Weber et al., 2010)
Triggering Rapid Mass Movements 2 (TRAMM2) (*)	(Lucas et al., 2020), (Lucas, 2019)
Performance of a bridge pier subjected to flood-induced foundation scour	(Ciancimino et al., 2021)

(*) funded by the ETH Competence Centre for Environment and Sustainability (CCES)

4.8 Reference Papers

1- Askarinejad, A., Laue, J., Zweidler, A., Iten, M. (2012). Physical modelling of rainfall induced landslides undercontrolled climatic conditions. Eurofuge 2012. https://doi.org/urn:nbn:se:ltu:diva-67929

2- Askarinejad, A, & Springman, S. (2014). Centrifuge modelling of the effects of vegetation on the response of a silty sand slope subjected to rainfall. In Computer Methods and Recent Advances in Geomechanics (pp. 1339–1344). CRC Press. https://doi.org/10.1201/b17435-236

3- Askarinejad, A. (2013). Failure mechanisms in unsaturated silty sand slopes triggered by rainfall [ETH Zürich]. https://doi.org/https://doi.org/10.3929/ethz-a-010002526

4- Ciancimino A., Jones L., Sakellariadis L., Anastasopoulos I., F. S. (2021). Experimental assessment of the performance of a bridge pier subjected to flood-induced foundation scour. International Journal of Physical Modelling in Geotechnics, in print.

5- Jones, L., & Anastasopoulos, I. (2020). Miniaturised tsunami generator to model interaction of tsunami with coastal infrastructure. International Journal of Physical Modelling in Geotechnics, 1–15. https://doi.org/10.1680/jphmg.19.00021

6- Lucas, D., Herzog, R., Iten, M., Buschor, H., Kieper, A., Askarinejad, A., & Springman, S. M. (2020). Modelling of landslides in a scree slope induced by groundwater and rainfall. International Journal of Physical Modelling in Geotechnics, 20(4), 177–197. https://doi.org/10.1680/jphmg.18.00106

7- Lucas Guzman, D. R. (2019). Seasonal Response of a Scree Slope [ETH Zürich]. https://doi.org/https://doi.org/10.3929/ethz-b-000377426

8- Morales Peñuela, W. F. (2013). River dyke failure modeling under transient water conditions [ETH Zürich]. https://doi.org/https://doi.org/10.3929/ethz-a-010088952

9- Taeseri, D., Laue, J., & Anastasopoulos, I. (2019). Non-linear rocking stiffness of embedded foundations in sand. Géotechnique, 69(9), 767–782. https://doi.org/10.1680/jgeot.17.P.201

10- Weber, T. M., Plötze, M., Laue, J., Peschke, G., & Springman, S. M. (2010). Smear zone identification and soil properties around stone columns constructed in-flight in centrifuge model tests. Géotechnique, 60(3), 197–206. https://doi.org/10.1680/geot.8.P.098

5 TU Delft Large Scale Geotechnical Physical Modelling Facility (Liquefaction Tank) (TU Delft)

5.1 Basic information

Table 11 collects some basic information about the facility.

Table 11 Basic information of TU Delft Large Scale Geotechnical Physical Modelling Facility

TU Delft Large Scale Geotechnical Physical Modelling Facility	
Name (short)	Liquefaction Tank
Name (long)	TD Delft Large Scale Geotechnical Physical Modelling Facility
Owner	Delft University of Technology
Location (City/Country)	Delft, the Netherlands
Address	Stevinweg 1, 2628 CN Delft
Website (vernacular language)	https://www.tudelft.nl/en/ceg/about-faculty/departments/geoscience-engineering/laboratory/facilities/static-liquefaction-tank-slt/
Website (English)	https://www.tudelft.nl/en/ceg/about-faculty/departments/geoscience-engineering/laboratory/facilities/static-liquefaction-tank-slt/
Contact (e-mail)	A.Askarinejad@tudelft.nl
Head of facility (name/e-mail)	Amin Askarinejad, A.Askarinejad@tudelft.nl
Construction year	2014

5.2 Scope of the facility

Liquefaction Tank consists of an instrumented inclinable container to investigate the susceptibility of loose sand seabed to flow slides triggered by sudden changes in the water level, fast sedimentation, scouring, or shock loads. The facility assures an ample range of applications ranging from offshore geotechnical engineering (e.g. submarine landslides and flowslides, dredging in sand layers), soil-structure interaction of shallow foundation, slope stability, dykes and embankments, soil vegetation interaction, unsaturated soil mechanics, and dynamic effects of geotechnical structures.

5.3 Facility physical description / Technical specifications

The Liquefaction Tank is a 2 m (width) × 2 m (height) × 5 m (length) inclinable structure composed of two main metal frames (upper and base frames), two glass sidewalls, and two metal end-walls (see Figure 38(a)).
The base frame enables the tank frame to be rotated. Four sets of base isolators under the frame are installed to prevent the possible external vibratory triggers. The isolators supporting the base frame only allow the passing of externally induced vibrations with frequencies well below the eigenfrequency of the very loose sand layers and slopes. A pair of hinges and jack-up screws connect the base frame to the tank frame. The liquefaction tank is equipped with a fluidization system to prepare the uniform sand bed in a loose and uniform state with a thickness ranging from 0.1 to 1.5 m. The sand bed in the liquefaction tank can be further prepared by controlled dredging of a slope through a Venturi-based suction dredging system (Figure 38(b),(c) and Figure 40). The liquefaction tank has been designed to test several types of failure triggers such as tilting, a shock load on the crest of the submerged slopes, and controlled pressure injection from the base of the tank (Figure 39). Two wave absorbers consisting of 6 fibrous PPC layers are installed at both ends of the Liquefaction Tank to absorb shallow waves (Figure 40).

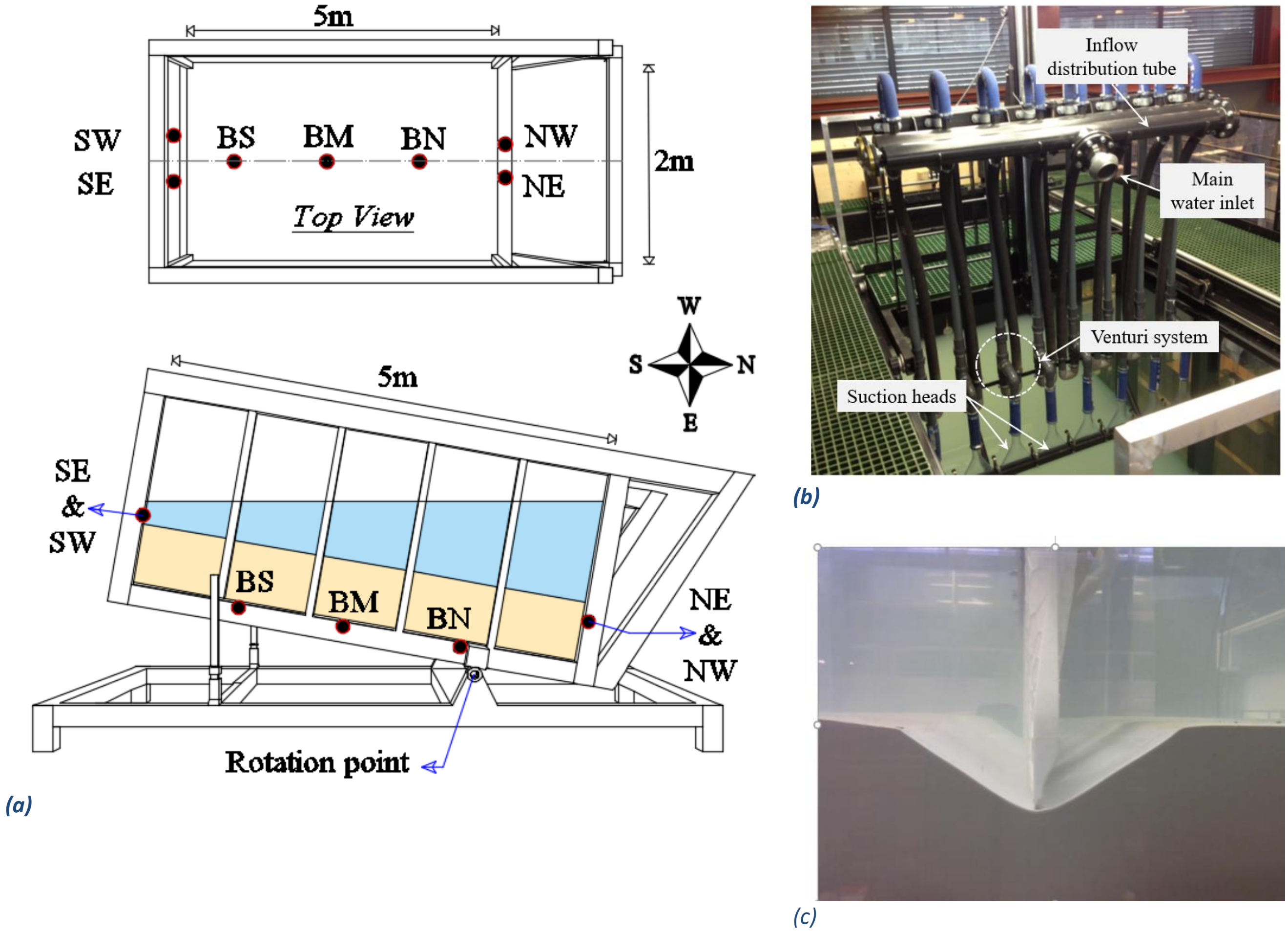


Figure 38. Schematic representation of the structure of the Liquefaction Tank
(a) and details of the dredging system (b), (c) [Maghsoudloo et al. 2018, 2017, De Jager et al. 2017, De Jager 2018]

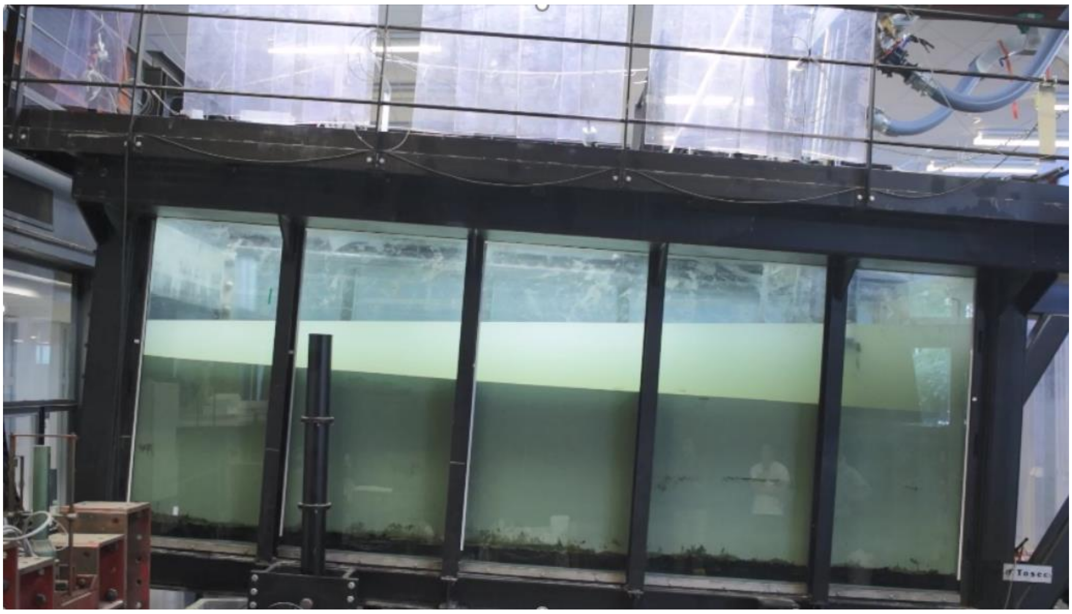


Figure 39. Liquefaction tank during tilting with a uniform seabed [Maghsoudloo et al. 2018, 2017, De Jager et al. 2017, De Jager 2018]

Figure 40. Submersed slope in the Liquefaction Tank prepared with the suction dredging system and the shallow waves absorbers

5.4 Sensors and instrumentation used in the facility

The experimental set-up includes various types of fixed and mobile sensors and actuators, which are all connected to the total data acquisition and control system. The data recorded by these sensors can be monitored in real-time on a computer screen and stored to disk using a data acquisition system. The developed data acquisition system allows for a switchable sampling rate code for all the 68 channels to alter the sampling rate from low (1Hz) to high (100 kHz) to optimize the size of recorded data files. The controlling system includes a hardware trigger input for instantaneous change of the sampling rates at the time of failure as well as a hardware trigger output to start the digital industrial stereoscopic cameras for visual inspection of the deformations and image analyses. The system is integrated by a high speed, high-resolution side camera for image analysis. Table 12 offers a short overview;all the sensors and instrumentation are regularly updated and calibrated in-house and are traceable to (inter)national standards.

Table 12. Sensors and instrumentation for the Liquefaction Tank

Physical magnitude to be measured	Type of sensor	Description	Range measurement	Accuracy
Pore pressure	KELLER PR-25Y	Piezo-resistive pressure transmitters installed at the bottom of the tank	0-50 kPa	± 0.02 kPa
	MPX4250A	Water pressure electronic sensor	0-50 kPa	± 0.075 kPa
	GDS	Differential pressure transducers between the fluidisation tubes and the base	69	0.25 % of the FS*
Acceleration	ADXL327	3 axis accelerometer chip	-1 to 1 g	± 0.005g
	Schaevitz, A710 single axis, A720 dual-axis (Sherborne)	Installed on the frame	-0.5 to 0.5 g	0.2 % of the FS
Total stress	In house	Compensated load sensors that measure the total pressure on a pressure plate	0-50 kPa	0.2% of the FS

Physical magnitude to be measured	Type of sensor	Description	Range measurement	Accuracy
Load	2430-BTH-5k-B (Interface)	load cells for the pressure plate in one of the triggering mechanisms	22 kN	0.1 % of the FS
Inclination	IS40 (Kubler)	Inclinometer cells for the pressure plate in one of the triggering mechanisms	± 60 deg	0.5 % of the FS
Temperature	JUMO, 90.252	Temperature sensors to measure the ambient temperature	0-60 °C	Class B (± 0.3 deg)
Flow	OPTIFLEX 2100C (Krohne)	Flow meter	0-20 lit/sec	0.5 % of the FS
Inclination	IS40 (Kubler)	Encoder of the motor that measures the inclination of the tank	0-26 deg	0.5 % of the FS
Water level	Level switch, Mobrey MINISQUING (Econosto)	Level detectors used for detection and prevention of overflow in the waters supply and filtering system	0-150 cm	

*FS: full scale

5.5 Test description

5.5.1 Type of tests/Problems that can be explored

Recent studies in the Liquefaction Tank have been focusing on static liquefaction of submarine slopes in loosely packed sand layers and scour protection to prevent static liquefaction induced flow slides. Nevertheless, the Liquefaction Tank can assure an ample range of applications ranging from offshore geotechnical engineering, soil-structure interaction of shallow foundation, slope stability, dykes and embankments, soil vegetation interaction, unsaturated soil mechanics, and dynamic effects of geotechnical structures.

5.5.2 Material suitable for the tests

The Liquefaction Tank uses Geba sand as standard test material. Geba sand is a fine crystal, quartz sand with a SiO_2 content of 99%. Table 13 summarizes the main properties of Geba sand (ASTM, 2007; Japanese Standard, 2009).

Table 13. Main properties of Geba sand

Parameter	Value
Particle shape	Sub-rounded
Specific Gravity	2.67
D_{50} (μm)	112
D_{10} (μm)	85
D_{60} (μm)	125
C_u, Uniformity coefficient	1.12
C_c, Coefficient of curvature	1.14
Minimum void ratio, e_{min}	0.64
Maximum void ratio, e_{max}	1.07

5.5.3 Test system limitations and constraints

- Test set-ups will not be installed before approval by TU Delft staff
- Tests will not be performed without TU Delft staff
- All test set-ups should be designed to perform within the parameters of the Liquefaction Tank
- The test will not be performed with materials that can cause hazards for health and/or environments

5.6 Examples of results/Relevant projects performed in the facility

Research project of "**Assessing Liquefaction Flow Slides Beyond Empiricism**". Researcher: De Jager, R. Financed by Netherlands Organization for Scientific Research.

The experimental part of the thesis includes the development of a novel, experimental facility: the liquefaction tank. It has been developed to produce high quality data of liquefaction flow slides for the evaluation of numerical models. This thesis addresses the performance of the liquefaction tank in terms of a consistent and reproducible replication of liquefaction flow slides. Liquefaction flowslides have been produced by conducting tilting tests of the level sand bed. The results allow the evaluation of the performance of the liquefaction tank, as well as the factors that influence the response of the sand bed.

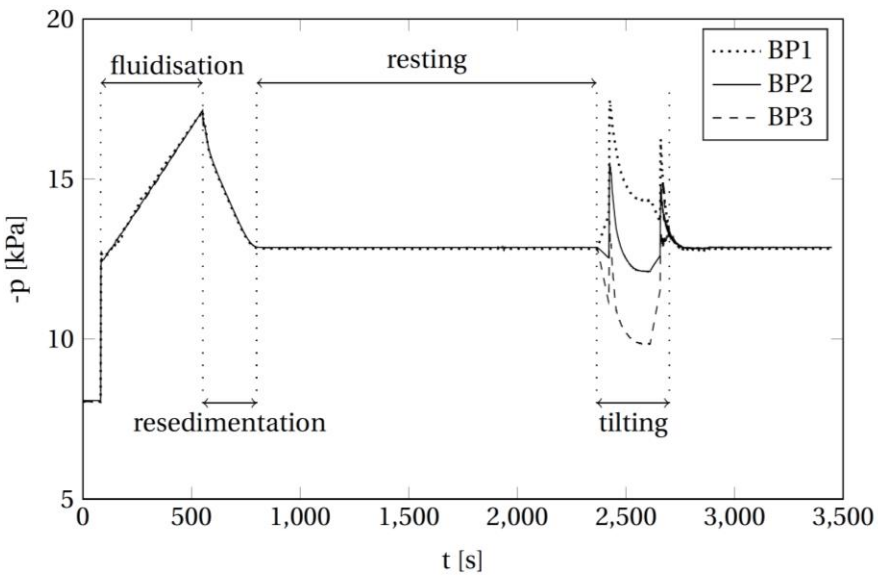


Figure 41. Measured pore pressures -p as a function of time for different stages of a tilting test (De Jager 2019)

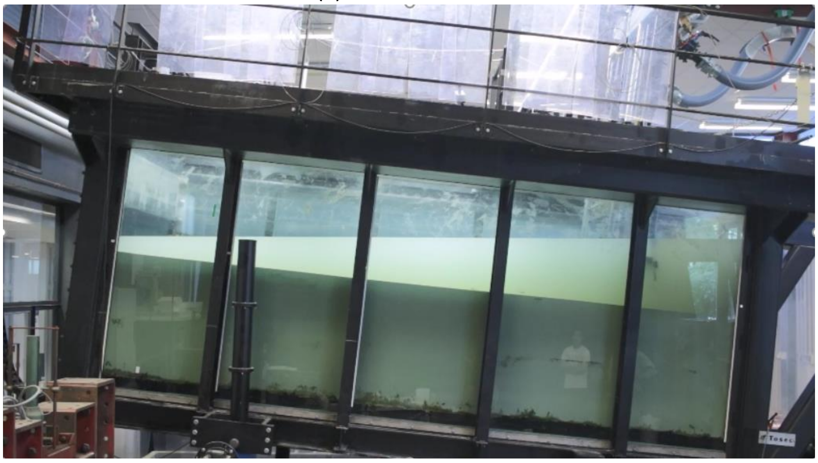
Research project of "**Role of scour protection on prevention of static liquefaction induced flow slides**". Researcher: Maghsoudloo, A. Financed by the Dutch Directorate-General for Public Works and Water Management (Rijkswaterstaat).

The Liquefaction Tank was used to investigate liquefaction-induced failures in submarine slopes. A fluidization technique was employed to reproduce homogenous sand flatbeds. To trigger static liquefaction, a tilting mechanism was used. The tank was tilted up to 10 degrees to the horizontal at a controlled fixed rate. The progressive inclination caused a change in the direction and magnitude of the effective stresses mimicking field phenomena as steepening of scour in slopes due to erosion or the stress change in the slope due to a local surficial failure. Some examples of the results of the tests are shown in Table 14.

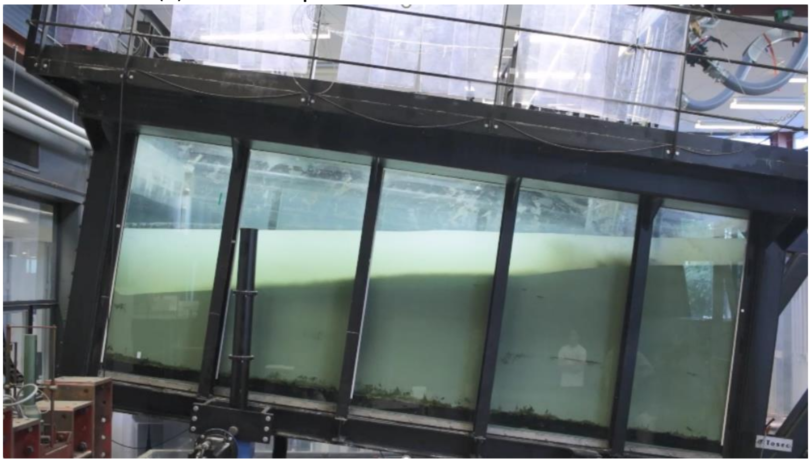
Table 14. Examples of the tests in the Liquefaction Tank at TU Delft
[Maghsoudloo et al. 2018, De Jager et al. 2017, De Jager 2018]

<u>Static liquefaction of submarine slopes:</u>

(a) Initial condition



(b) Tilted liquefaction tank and stable seabed



(c) Tilted liquefaction tank and liquefied seabed

Experimental investigation of submarine landslide induced tsunami waves (Filipouskaya, 2019).
Within the scope of this project a number of experimental simulations on submarine slope failures were conducted in the liquefaction tank – a unique testing facility for large scale experiments at the Geo-Engineering Laboratory of TU Delft. To improve the understanding of tsunami generation, this study focused on the moment of onset of a

submarine slope failure, aiming to capture the instant of wave generation as well as to link the processes within a failing soil mass.

The significant novelty of this study was its multidisciplinary approach, as the landslide and the process of wave generation were observed from a point of view of geotechnical and hydraulic engineering, aiming to join both disciplines to better understand the complex nature of tsunami generation. In this study the focus was mainly on physical modelling, developing a suitable experimental set-up for wave generation by submarine slope failure, performing a number of laboratory experiments and conducting analysis of obtained data. With this study it is envisioned to provide a unique basis for a future research on nature of tsunami waves to allow better prediction of possible future disasters.

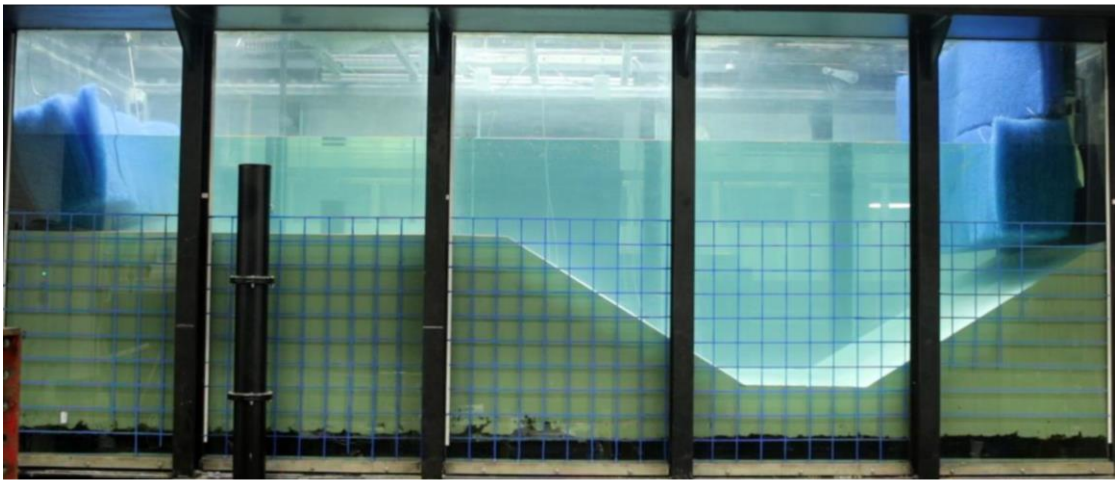


Figure 42. Test set up and the wave absorbers for the liquefaction tank (Filipouskaya, 2019)

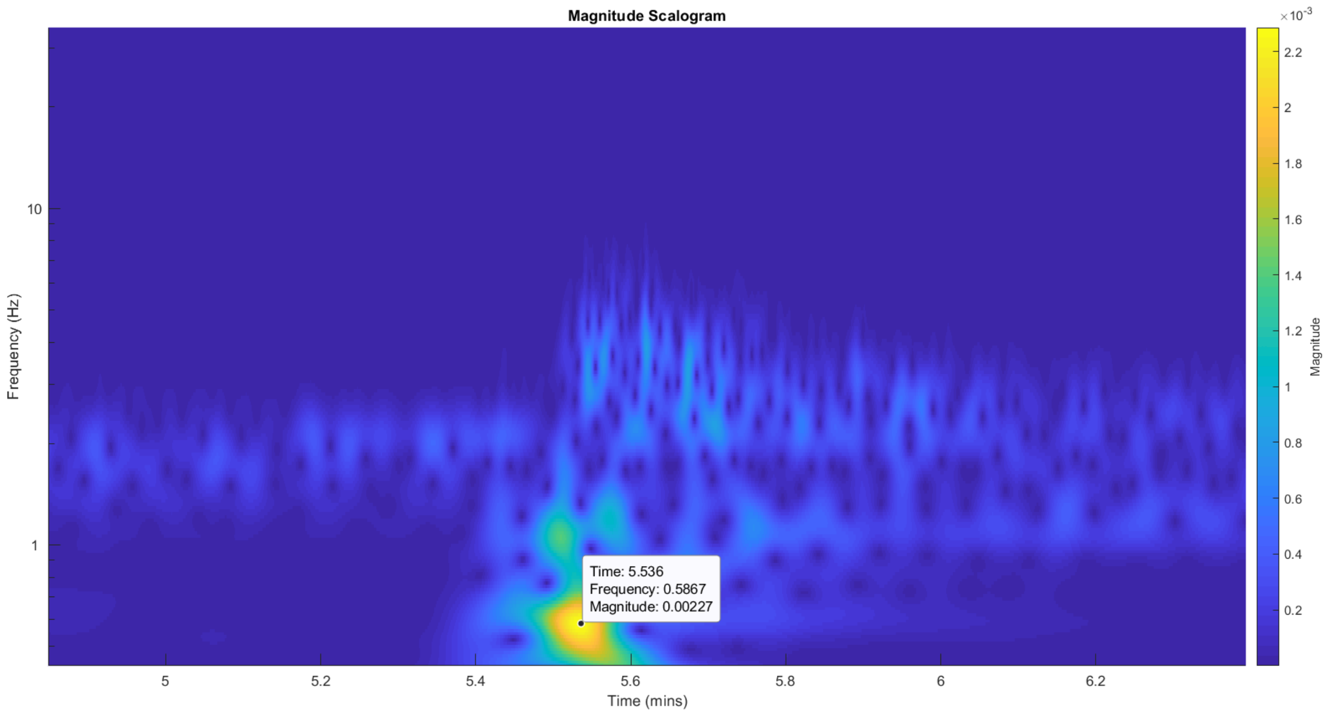


Figure 43. Continuous wavelet transform with Morse wavelet (Filipouskaya, 2019)

5.7 Reference papers

1- Zhang W., Askarinejad A. (2019). “Centrifuge modelling of submarine landslides due to static liquefaction” Landslides 16:1921-1938 doi:https://doi.org/10.1007/s10346-019-01200-z.

2- De Jager, R.R., Maghsoudloo, A., Askarinejad, A. & Molenkamp, F. (2017). Preliminary results of instrumented laboratory flow slides. In 1st International Conference on the Material Point Method, Delft, The Netherlands, Elsevier Ltd, 212-219, doi: http://dx.doi.org/10.1016/j.proeng.2017.01.012.

3- De Jager, R. (2018). “Assessing Liquefaction Flow Slides: Beyond Empiricism”. PhD thesis Delft University of Technology https://doi.org/10.4233/uuid:51df13ed-6ba0-49ba-99d7-1c14f8fd022e.

4- Filipouskaya, N. (2019) Experimental investigation of submarinelandslide induced tsunami waves. MSc thesis, TU Delft.

5- Maghsoudloo, A., Askarinejad, A., de Jager, R., Molenkamp, F. & Hicks, M. (2018). Experimental investigation of pore pressure and acceleration development in static liquefaction induced failures in submerged slopes,Physical Modelling in Geotechnics, Volume 2 (pp. 987-992), CRC Press (Pub).

6- Maghsoudloo, A., Galavi, V., Hicks, M. & Askarinejad, A. (2017). Finite element simulation of static liquefaction of submerged sand slopes using a multilaminate model. In 19th International Conference on Soil Mechanics and Geotechnical Engineering, Seoul, 2:805-808.

7- MAGHSOUDLOO, A. ASKARINEJAD, A. DE JAGER, R. MOLENKAMP, F. HICKS & M. 2020. Large-scale physical modelling of static liquefaction in gentle submarine slopes, Landslides, Under review.

8- MAGHSOUDLOO, A., ASKARINEJAD, A., DE JAGER, R., MOLENKAMP, F. & HICKS, M. 2018a. Experimental investigation of pore pressure and acceleration development in static liquefaction induced failures in submerged slopes. Physical Modelling in Geotechnics, Volume 2. CRC Press.

9- MAGHSOUDLOO, A., GALAVI, V., HICKS, M. & ASKARINEJAD, A. 2017a. Finite element simulation of static liquefaction of submerged sand slopes using a multilaminate model. 19th International Conference on Soil Mechanics and Geotechnical Engineering. Seoul.

10- Jager, R. and F. Molenkamp. (2012) “Fluidization system for liquefaction tank.”, doi: https://api.semanticscholar.org/CorpusID:54816411

5.8 Other relevant information

- Amount of material needed: Dry sand: ~ 10 m^3
- Test duration: 1 to 2 weeks (including the model preparation)
- Type of format result delivers to the client: CSV files
- Connection with other TA providers: a small scale of this tank has been developed for the geotechnical centrifuge at TU Delft (Zhang and Askarinejad, 2019)

6 Uni-Eiffel Geo-Centrifuge (Uni Eiffel)

6.1 Basic information

Table 15 collects some basic information about the facility Uni-Eiffel Geo-Centrifuge.

Table 15 Basic information of Geo-Centrifuge (Uni Eiffel)

Uni Eiffel Geo-Centrifuge	
Name (short)	Centrif-UGE
Name (long)	Geotechnical Centrifuge of the University Gustave Eiffel
Owner	University Gustave Eiffel
Location (City/Country)	Uni Eiffel Nantes' Campus (Bouguenais/France)
Address	Allée des ponts et chaussées - CS 5004; F-44344 Bouguenais
Website (vernacular language)	https://www.univ-gustave-eiffel.fr/universite/nos-equipements-remarquables/
Website (English)	https://www.univ-gustave-eiffel.fr/en/the-university/our-exceptional-facilities/
Contact (e-mail)	centrif-nantes@univ-eiffel.fr
Head of facility (name/e-mail)	Matthieu BLANC matthieu.blanc@univ-eiffel.fr
Construction year	1985

Figure 44 shows a general view of the 200xg-ton Centrif-UGE.

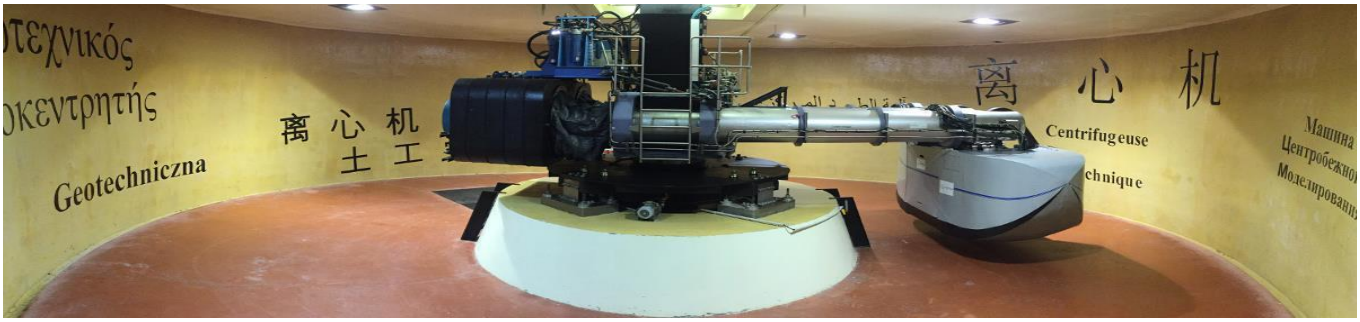


Figure 44 The 200×g-ton Centrif-UGE (5.5m radius)

6.2 Scope of the facility

The Centrif-UGE is devoted to physical modelling in geotechnics.
By increasing the centrifuge forces applied on a small-scale model of a geotechnical work, the stress field existing on full scale (prototype) geotechnical work is reproduced. The model is installed in the Centrif-UGE's basket (~1.5m^3 of volume).
A set of scaling laws have been established (e.g. Garnier et al., 2007, doi.org/10.1680/ijpmg.2007.070301) for different applications.

The Centrif-UGE is versatile and offers a large domain of applications, concerning mainly soil-structure interaction (SSI):

- Piles, monopiles, piles group effect, helical piles under vertical/horizontal monotonic/cyclic loading
- Off-shore anchoring systems for Oil & Gas or Marine Renewable Energy
- Shallow foundations (e.g. in slope vicinity)
- Soft soils reinforced with vertical rigid inclusions
- Construction of adjacent embankments on soft soils; Reinforced earth structures (soil-nailed wall;

geosynthetic layers)
- Tunnels: effect of excavation on surface settlement
- Unsaturated soils
- Ground vibration isolation
- Cantilever wall
- Seismic loading, soil liquefaction (not detailed in this document)
- Macrogravity testing of medical apparatus or aeronautical devices (not detailed here).

Figure 45 shows a scheme of the Centrif-UGE.

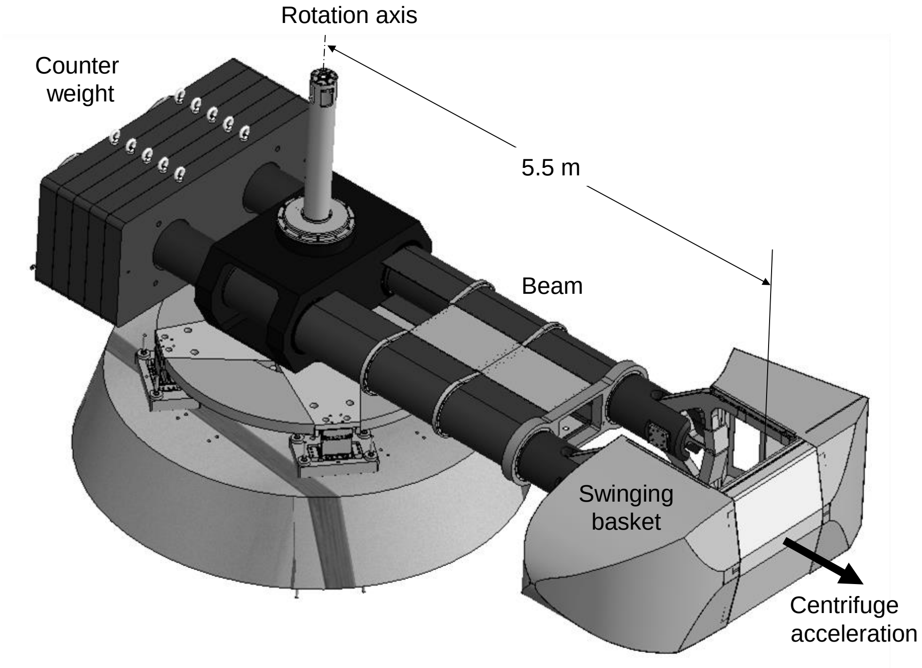


Figure 45 Scheme of the Centrif-UGE

6.3 Facility physical description / Technical specifications

The Centrif-UGE is one of the largest in the world, with a radius of 5.5m, a payload of 2t at 100g.

- Connections to the on-board scale model:
    - Electric, low-voltage rotary contact slip rings (101)
    - Rotary contact connector power (2A and 160A)
    - Optical rotary contact connector and optical fibre
    - Rotary joints (water, compressed air, hydraulic)
    - Digital cameras and image processing
    - Computer network
- Associated equipment:
    - Unidirectional earthquake simulator (not detailed in this document)
    - Four-axis remote operating robot system
    - Miniature geotechnical investigation tools (penetrometer, pressuremeter, cane test, T-Bar)
    - Hydraulic and electric servo actuators
    - Sensors set (~230) acquisition chains
    - Mobile pluviation hopper and consolidometers for test massif preparation
    - Transparent face containers
    - Roll-motion simulator

- Mobile tray for investigating the load transfer behavior towards rigid inclusions
- In-flight saturation

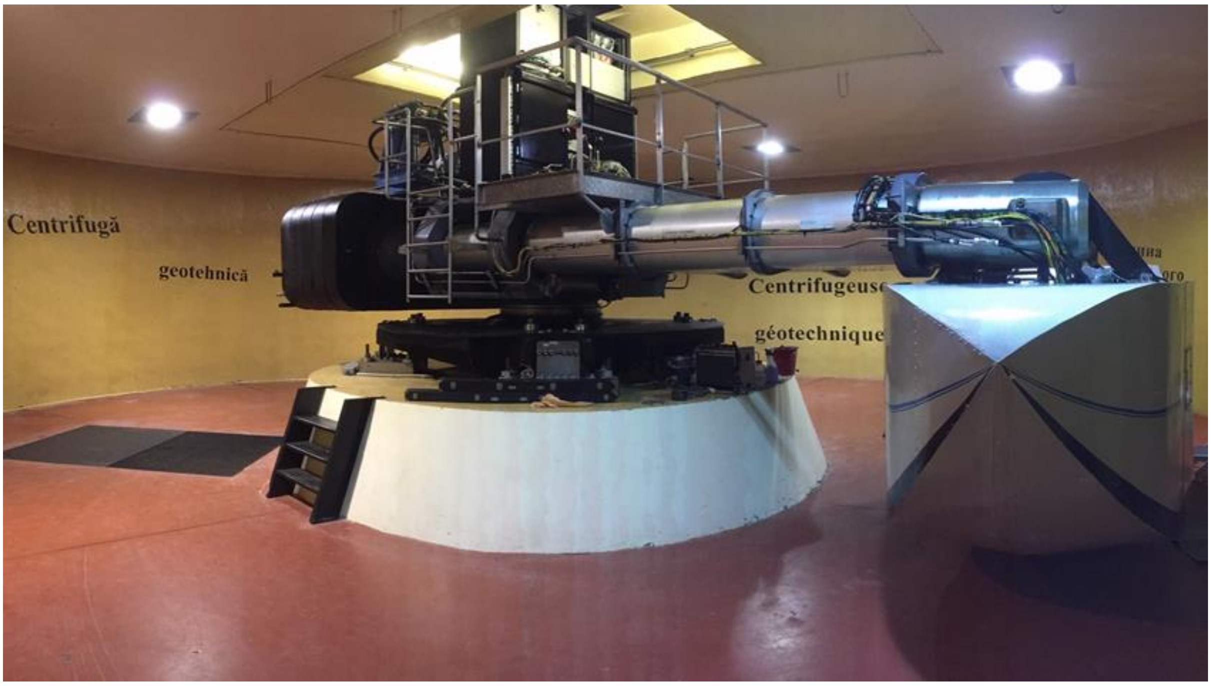
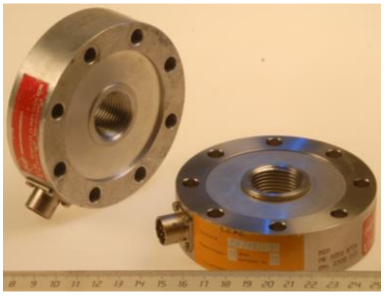


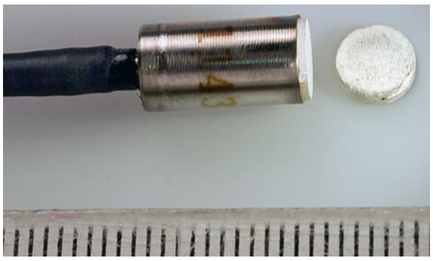
Figure 46 The Centrif-UGE, since 1985

6.4 Sensors and instrumentation used in the facility

Table 16 Sensor and instrumentation of Centrif-UGE

Physical magnitude to be measured	Type of sensor	Description / picture	Range measurement	Number
	LVDT	Trademark: Sensorex and HBM 	Different models with a measuring range between 20 to 75 mm	8
	Potentiometer	Trademark: MCB 	Different models with a measuring range between 50 to 150 mm	40
Displacement	Magneto strictive	Trademark: TWK 	Different models with a measuring range between 75 to 400 mm	6

Physical magnitude to be measured	Type of sensor	Description / picture	Range measurement	Number
	Ultrasonic	Trademark Wenglor 	2 different models with a range of 400 mm	2
	Laser	Trademark: Wenglor, Baumer and some frome microepsilon with a frequency of 10 000 Hz 	Different models with a range between 10 to 350 mm	22
	potentiometer	Trademark: MCB 	305°	5
Rotation	codeur	Trademark Kubler	360°	1
	Gage sensors with wafer shape	Trademark: FGP, TME, Measurement Specialities Different diameters: 30, 60 or 100 mm 	Different models with a range between 50 to 2500 daN	20
	Gage sensors with cylinder shape	Different diameters 6, 8,10,12,20 mm	Different models with a range between 35 to 2000 daN	16
Force	Gages sensors multi-axes	A three axis (450 daN), a 2 axes (load and torque) and a 6 axis (loads and moments)	450 to 2500 daN depends of the model	3
Stress	Gage sensor	Trademark: Kyowa	200 kPa 500 kPa	10

Physical magnitude to be measured	Type of sensor	Description / picture	Range measurement	Number
				
Pore pressure	Gage sensor with filter	Trademark: Druck, Keller, Mesaurement Specialities 	100 kPa 300 kPa 700 kPa	40
Temperature	PT100			6
Accelerometer	piezzo	Trademark: B&K	+- 500 G 20 kHz	40
Instrumented pile	FBGs inside groove	Pile instrumented by HBM		2
	strain gages inside	Piles of different diameters equipped with about 20 sensors		2
	strain gages outisde	Piles of different diameters equipped with about 20 sensors		10

Data Acquisition Systems:

- HBM quantumX:
  8 modules with 16 channels which are able to support technology of our sensors.
  Sample rate 20 KHz synchronize for all channels
  https://www.hbm.com/en/2128/quantumx-compact-universal-data-acquisition-system/
- HBM Braggmeter FS22
  Optical measurement to interrogate Fiber Bragg Grating (FBG) based sensor with 6 channel wich can be composed of about 20 sensors
  Sample rate of 1000 sample/s
  https://www.hbm.com/en/4604/fs22-industrial-braggmeter-optical-interrogator/
- LMS Scadas
  2 modules Scadas mobile with 96 channels which are able to support technology of our sensors
  Sample rate 50kHz synchronize for all channels
  https://www.plm.automation.siemens.com/global/fr/products/simcenter/scadas-mobile.html

Software:

- Cataman (HBK) to control visualize and save data from modules QuantumX
- LMS Test Express to control, visualize, and save data from LMS Scadas mobile

Network: ethernet LAN at 1 Gb/s between the control room and the basket of the centrifuge.

6.5 Test description

6.5.1 Type of tests/Problems that can be explored

The Centrif-UGE and its ancillary equipment offer a large range of testing possibilities:
- Loading with actuators: monotonic/cyclic + vertical/horizontal/inclined
- Multiphase operations using the 4-axes robot: excavation program, soil consolidation, combination of loading tools and investigation tools

The collection of actuators used inflight in the Centrif-UGE offers different strokes and force ranges.

The boundary conditions are given by the limits of the strongboxes in which the soil model is reconstituted.

6.5.2 Material suitable for the tests

A. Actuators

The collection of actuators used inflight in the Centrif-UGE are:
- Servo actuator & support n°1: force 32kN, stroke 70mm
- Servo actuator & support n°2: force 32kN, stroke 300mm
- Servo actuator & support n°3: force 32kN, stroke 450mm
- Electric Servo actuators:
  - EXLAR GSX50 Stroke: 150mm, Continuous Force rating: 800daN
  - EXLAR GSX30 Stroke: 150mm, Continuous Force Rating: 300daN
- Impact driving actuator (IDA): max. acceleration 100×g, max. stroke 25mm, prototype energy 3MJ (at 100×g)

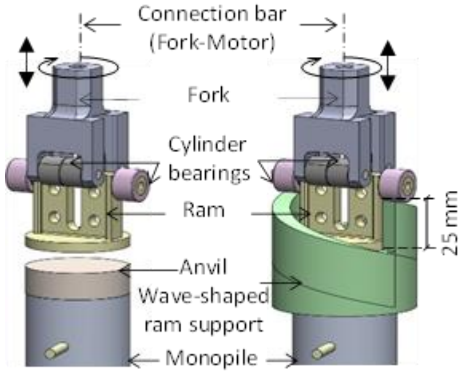


Figure 47 Scheme of the IDA for monopile

B. Containers

The boundary conditions are given by the limits of the strongboxes in which the soil model is reconstituted. Four families of boxes are used in the Centrif-UGE:
- Rectangular strongboxes:
  - a) 1.2m length × 0.8m width × 0.12 height (2 elements) or 0.24 (2elts) or 0.36 (5elts) or combination of the previous ones to give the heights 0.48 or 0.60 or 0.72m;
  - b) 0.65m length × 0.5m width × 0.4 height for in-floght saturation
- Circular tub:
  a) Ø 0.89m h 0.7 (3 elements), 0.36 (2 elements), 0.31 (1 element), 0.2 (1 element), 0.16m (1 element)
  b) Ø 0.3m h 0.3m (6 elements)
  c) Ø 0.41m h 0.3m (1 element)

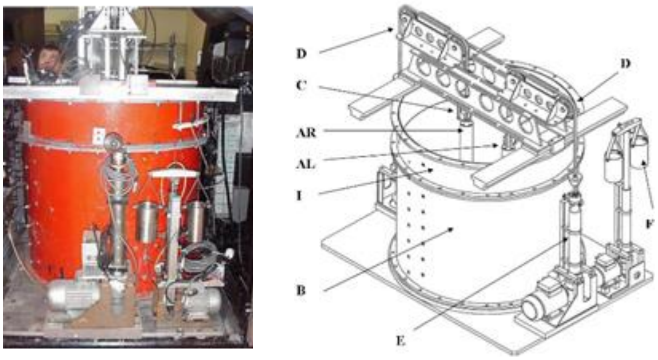


Figure 48 Set up for suction caisson tests @ 100xg

- Transparency side containers:
    a) 0.8m × 0.4m × 0.36m
    b) 0.8m × 0.45m (assembled with “removable U parts” of width 0.2m,0.15m,0.1m)× 0.45m

Figure 49 Preparation of a test of wetting-induced collapse in embankment base

C. Robot

<u>Characteristics of the Robot are:</u>

- Stroke axe X: 560mm, axe Y: 978mm, axe Z: 400mm, Rotation Z: 370°
- Speed axe X: 0 to 80mm/s, axe Y: 0 to 50mm/s, axe Z: 0 to 50mm/s
- Maximum Force X: 100daN, Y : 25daN, Z : -450daN/500daN

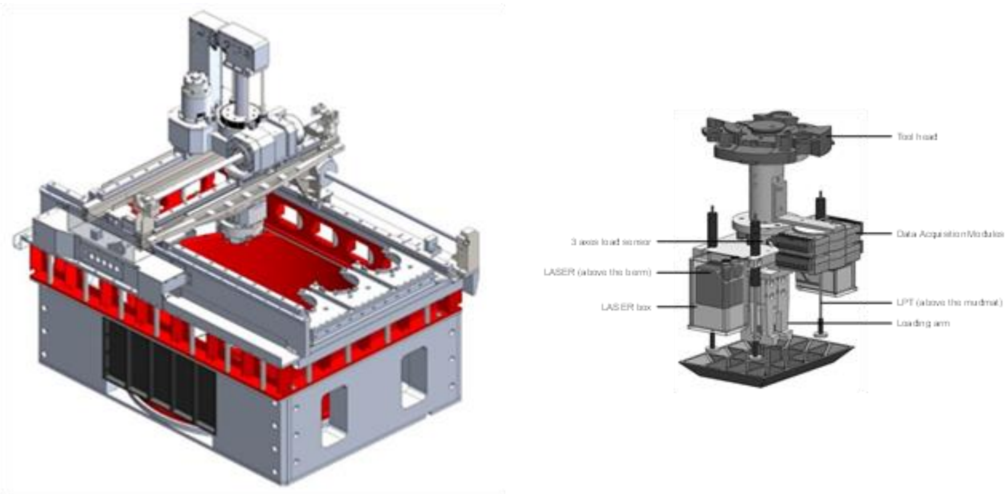


Figure 50 Four-axes robot over a Ø 0.89m circular container (left). Tool designed for PLET sliding foundation (right)

<u>Robot & its tools:</u>
The robot has a magazine with three tools emplacements where it can dispose:
A - CPT tool
B - T-Bar tool
C - Pincer tool
D - Or tools developed specially for specifics used

A B C D

Figure 51 Tools that can be disposed in the robot

D. Mobile Tray Device (MTD)

The MTD simulates the vertical settlement of soft soil, inducing the punching of the Load Transfert Platform (e.g. sand layer) by the (up to) 61 Rigid Inclusions. French National Projet ASIRI (2005-2012)

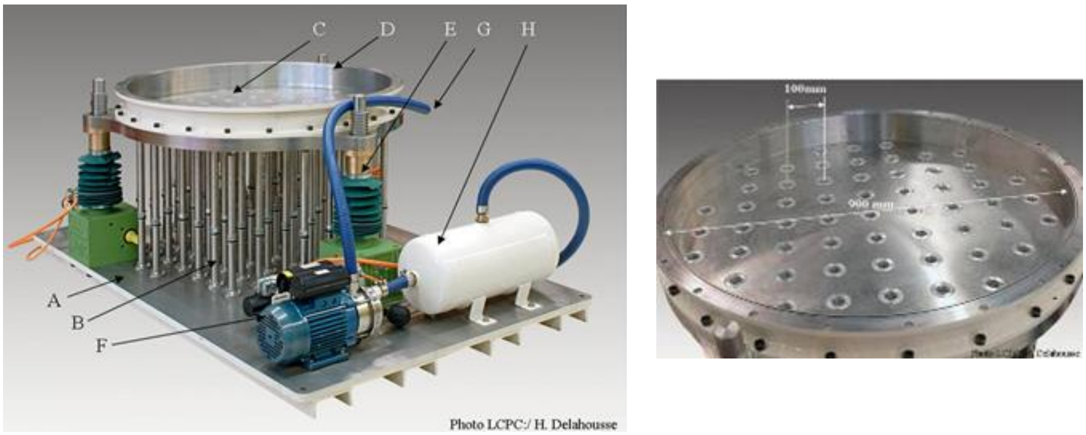


Figure 52 Mobile Tray Device

E. Rolling test device

It simulates the rolling movement of ore cargo during maritime shipping, in order to study the liquefaction induced phenomena (Eranet Martec Liquef Action, 2014-22018). Max. g-level: 80, max. angular velocity 60°/s, max. rotation angle of rolling ±25°.

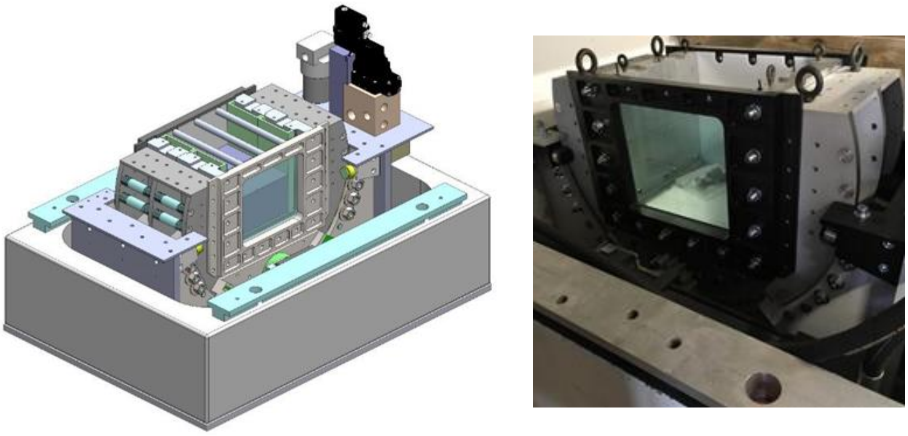


Figure 53 Rolling test device

F. Soils

- Clean sand (Fontainebleau NE34 or Hostun HN34)
- Industrial clay (Speswhite clay) is generally used, but site soils can be prepared for special reconstitutions.

G. Soil preparation

- Model-construction sand hopper equipment
- Soil consolidation system for circular container Ø 0.89m
- Soil consolidation system for circular container Ø 0.3m
- Soil consolidation system for rectangular container
- Depressurized clay mixer
- 1×g big sand hopper
- Mini sand hopper
- On-board embankment construction sad hopper

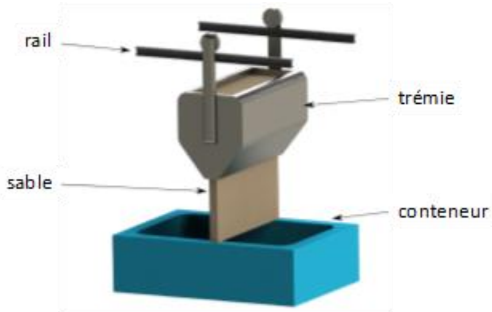


Figure 54 Scheme of the sand hopper

H. Soil investigation:

- On-board cone penetrometer
- On-board vane apparatus
- On-board T-bar
- On-board pressuremeter

6.5.3 Test system limitations and constraints

The limitations of the use of the Centrif-UGE are:

- The size of the small-scale model
- The size of the instrumentation

- The validation of the sensors' technology

The application of the scaling laws which may consider sometimes only the main phenomena.

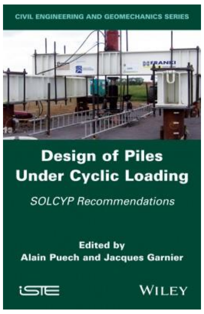
However, the know-how is important thanks to experience accumulated in more than thirty-five years by the Centrif-UGE team.

6.6 Examples of results and Relevant projects performed in the facility

The Centrif-UGE offers the opportunity to complete other approaches used in research and engineering, such as numerical simulations or field tests. As the small scale models are instrumented, as their boundary conditions are well-known, as the soil is generally a standard one and as the loads may reach ultimate loading, the Centrif-UGE test offers the possibility to observe, to understand, to collect experimental data and to perform parametric studies. This is why the Centrif-UGE contribution has been appreciated is several collaborative researches, as well as in the academic field and with practitioners.

6.6.1 Piles subjected to cyclic loading

- SOLCYP recommandations 2017



- ANR SOLCYP+ (2017-2020): monopiles

6.6.2 Soft soil reinforcement with vertical Rigid Inclusions

- Rion-Antirion Bridge
- National Project PN ASIRI (2005-2012), ASIRI recommendations 2012

- National Project PN ASIRI+ (2020-2024)
- ANR ASIRIplus_SDS (2019-2024)
- Mobile Tray Device

6.6.3 Off-shore geotechnics

- ANR SOLCYP+ (2017-2020): monopiles
- Weamec-Redenv-eol (2017-2021): Helical piles
- Pile driver
- In-flight sand saturation

- Fiber Optic intrumentation on monopile
- Suction caissons (in flight installation + V or H loading)
- Helical pile
- Sliding foundation for PLET

6.6.4 Miscelaneous

- French standards of Shalllow foundations in the vicinity of slopes
- Nailed walls
- Shallow foundation swipe test
- Roll-motion simulator for maritime cargo transport

6.6.5 Installation schemes for pile testing under vertical or horizontal loading

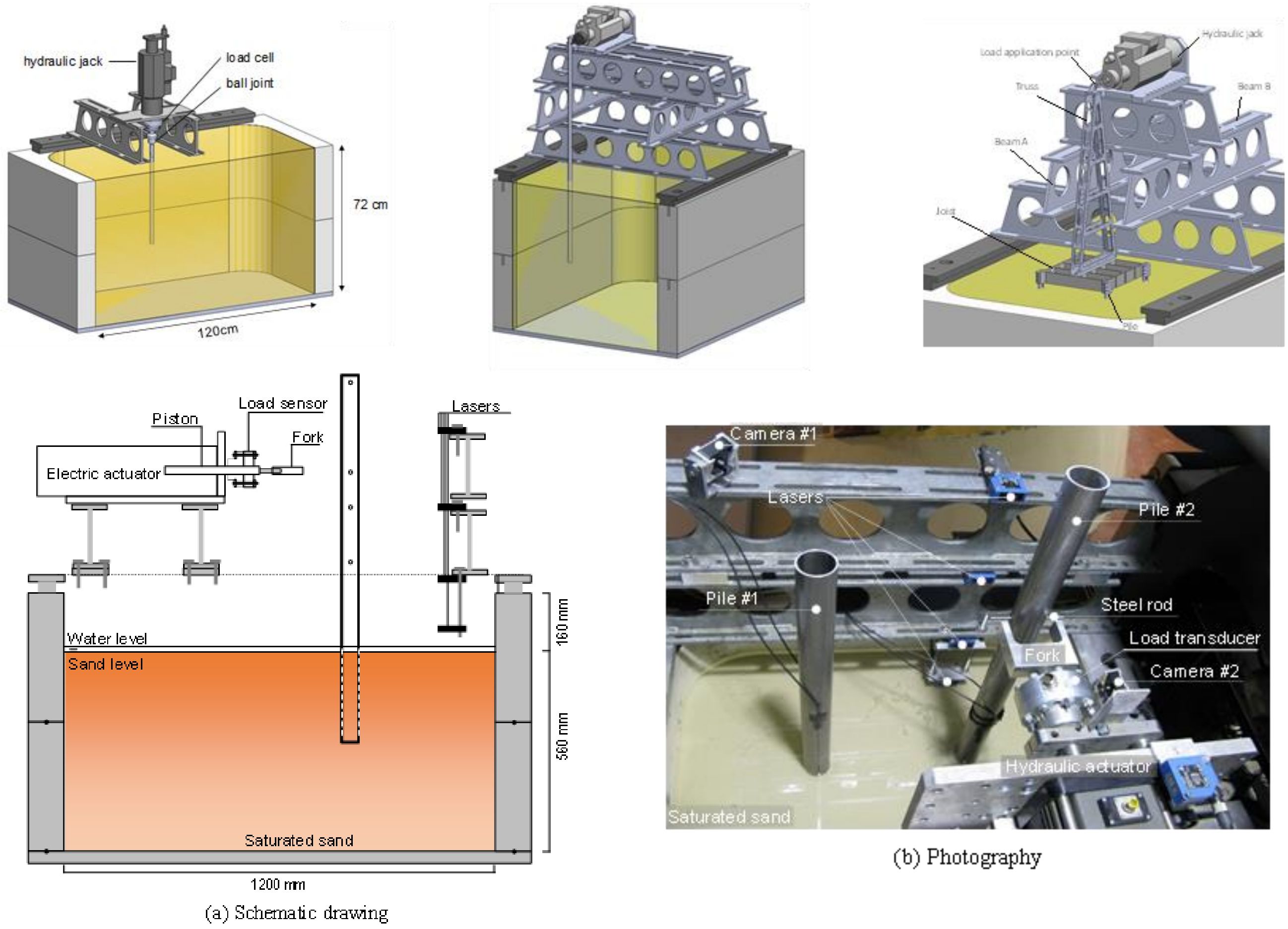


Figure 55 Installation schemes for pile testing under vertical or horizontal loading

6.6.1 Device for installation by impact driving followed by cyclic lateral loading

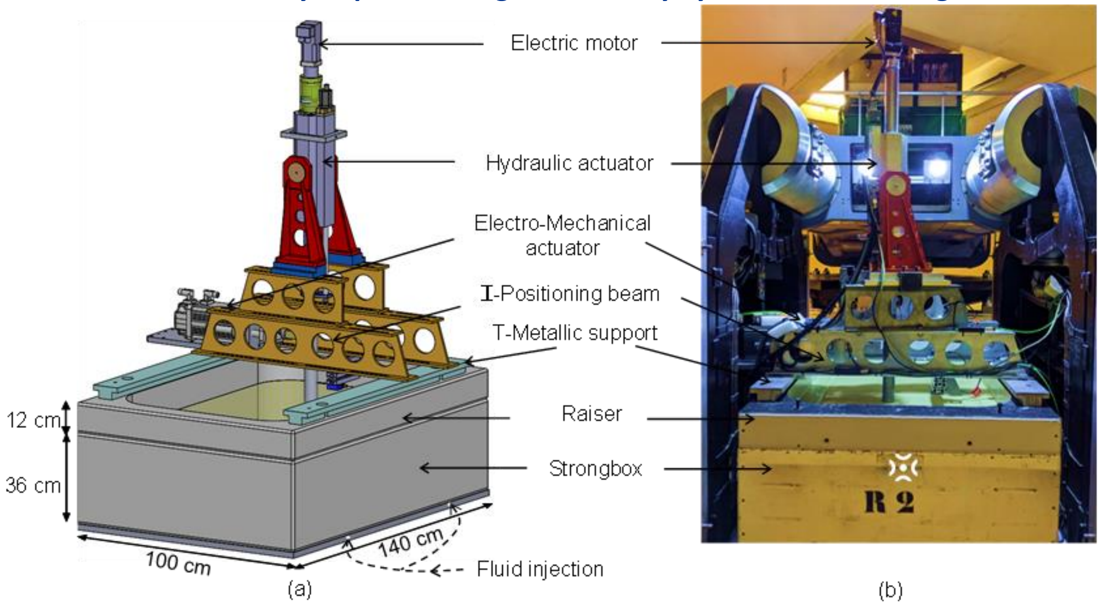


Figure 56 Device for installation by impact driving followed by cyclic lateral loading

6.7 Reference papers

1- Thorel L., Rault G., Garnier J., Murillo C., Gaudicheau P., Néel A., Favraud C. 2008 Macro-gravity measurements on reduced-scale models of geotechnical structures. Bulletin de liaison des Ponts et Chaussées ISSN 1269-1496, n° 272-273 spécial Métrologie pp93-131.

2- Chazelas J.-L., Escoffier S., Garnier J., Thorel L., Rault G. 2008 Original technologies for proven performances for the new LCPC earthquake simulator. Bulletin of Earthquake Engineering. Vol.6 n°4 ISSN1570-761X. pp723-728. doi :10.1007/s10518-008-9096-z

3- Blanc M., Thorel L, Girout R. Almeida M. 2014 Geosynthetic reinforcement of a granular load transfer platform above rigid inclusions: comparison between centrifuge testing and analytical modelling. Geosynthetics international. February 2014 ,Vol.21, 1, pp.37-52. DOI: 10.1680/gein.13.00033 “the best paper for 2014. Honourable mention”

4- Gaudicheau P., Thorel L., Néel A., Audrain Ph., Lozada C., Monroy J. 2014 Improvement of the IFSTTAR robot control system, 8th ICPMG Int. Conf. on Physical Modelling in Geotechnics, Perth 14-17 january, pp.221-226.

5- Blanc M., Thorel L. 2016 Effect of cyclic axial loading sequences on piles in sand. Geotechnique Letters, 6(2), 163–137, https://doi.org/10.1680/jgele.15.00155.

6- Schiavon J.A., Tsuha C.H.C., Thorel L. 2017. Cyclic and post-cyclic monotonic response of a single-helix anchor in sand. Geotechnique letters 7, 11-17, http://doi.org/10.1680/jgele.16.00100

7- El Haffar I., Blanc M., Thorel L. 2017 Impact of pile installation method on the axial capacity in sand. Géotechnique Letters, 7, 260-265, http://doi.org/10.1680/jgele.17.00036

8- Lalicata L., Casini F., Thorel L., Desideri A. 2018 Experimental observation on a laterally loaded pile in unsaturated silty soil Canadian Geotechnical J. (published on line 17th nov.2018). https://doi.org/10.1139/cgj-2018-0322 vol. 56: 1545–1556 (2019).

9- Li Z., Blanc M., Thorel L. 2019. Using Fibre Bragg Grating Sensors to estimate the horizontal response of a monopile in geotechnical centrifuge (IJPMG, published on line on 21st nov. 2019) https://doi.org/10.1680/jphmg.19.00022

10- Maatouk S., Blanc M., Thorel L. 2020 Development of a hammer to drive monopiles wind turbines in centrifuge. 4th European Conference on Physical Modelling in Geotechnics, Lulea 15-17 march. Postponed to sept. ECPMG2020, Laue & Bansal (eds.) ISBN 9789177904531, 89-93.

6.8 Other relevant information

The Centrif-UGE is programmed **week per week**, one week corresponding to one research project. This allows to install the devices in the centrifuge (small scale model, loading systems, instrumentation connection,…).

The duration of one test varies a lot between few seconds for a seismic shot and few days for thick clay models.

Depending on the complexity of the expected tests, the design phase requires more or less time. Usually, a minimum delay of 6 months is required for scheduling the test.

The four other teams equipped with a geo-centrifuge are the people who do the same job than us. So easy connection is possible for complementary tests.

7 GeoModel container (DELTARES)

7.1 Basic information

Table 17 collects some basic information about the facility.

Table 17 Basic information of the GeoModel container facility

GeoModel container	
Name (short)	GeoModel container
Name (long)	GeoModel container
Owner	Stichting Deltares
Location (City/Country)	Delft/The Netherlands
Address	Boussinesqweg 1, 2600 MH, Delft, The Netherlands
Website (vernacular language)	https://www.deltares.nl/en/facilities/geo-model-laboratory/
Website (English)	https://www.deltares.nl/en/facilities/geo-model-laboratory/
Contact (e-mail)	Rob.Zwaan@deltares.nl ; Jarno.Terwindt@deltares.nl
Head of facility (name/e-mail)	Harm Aantjes / Harm.Aantjes@deltares.nl
Construction year	1985

7.2 Scope of the facility

This facility compromises of a rigid model container with loading and measurement systems. It can be used for studying soil behaviour and the interaction with structures using accurately prepared sand and clay models. With the GeoModel container full-scale models can be built and tested under laboratory conditions.

7.3 Facility physical description / Technical specifications

The GeoModel container measures 4 x 2.5 x 1.2 m (l x w x h), however, this container can be downsized if required. The container itself is very flexible and virtually any test that requires a sand bed up to 4 x 2,5 x 1,2m (l x w x h) can be performed. The container is equipped with a fluidisation system for building homogeneous sand models at the required density. Several other containers, both for atmospheric pressure and elevated pressure (several bars), are also available. The staff on the facility has experience in making homogeneous or deliberately layered soil samples. The container allows for phreatic flow or confined groundwater flow. Effective stress at large depths can be simulated using different air pressure levels. The sand bed can be liquified and/or densified to required specifications. An excavator is available for quickly replacing sand if needed. In additions, the Deltares workshop is able to design and manufacture items required for tests in the container.

The infrastructure is equipped with a new HBM QuantumX data acquisition system that can sample up to 100ks/sec. For data processing systems as Matlab, Python, and the standard CATMAN AP software package of HBM can be used. Data output can be delivered in 17 formats such as BIN, CSV, MATHLAB, ASCII and TXT format.

A photo of the GeoModel container is given in Figure 57.

Figure 57 The Deltares GeoModel container

An overview of the systems, utilities and equipments that are available for the GeoModel container is given in Table 18 together with a brief description of their technical specifications.

Table 18 Overview of the GeoModel container systems/utilities/equipment

Systems/Utilities/Equipments	Description
Cameras	Several camera systems are available, from time lapse to high-speed frame rates and from 5Mp to 42Mp
Excavator	Hydraulic excavator for quick excavations and/or moving material in the container
Hydraulic pressure system	Hydraulic actuators available for performing several actions such as CPT measurements
Pressurized air system	6 bar pressurized air available
Vacuum system	Down to 50mBar vacuum available
Normal & de-aired water	2 separate supply lines available for normal and de-aired water
Utility frames to hold plungers	Large frames over the container can be used for hoisting and/or mounting purposes
Data acquisition system	HBM QuantumX system with CatMan AP software
Deltares workshop	For the design and manufacturing of necessary tools, instruments etc.

7.4 Sensors and instrumentation used in the facility

For the GeoModel container, a common and wide range of sensors is available. Table 19 provides a short overview of the parameters that can be measured. Since the instruments are regularly updated and/or replaced please check most recent possibilities when preparing tests. All sensors can be calibrated in-house and are traceable to (inter)national standards.

Table 19 Sensor and instrumentation for GeoModel container

Physical magnitude to be measured	Type of sensor	Description
Displacement	Displacement	Several types, brands, ranges and accuracies are available
Soil Pressure	Soil pressure	Several sizes, brand, types, ranges and accuracies are available
Force	Force transducers	Compression, Tension, several ranges, types and accuracies are available
Temperature	Temperature sensors	Pt100, Pt1000, Thermocouples
Pressure	Pressure sensors	(Soil)pressure sensors in several types, brands, ranges and accuracies are available

7.5 Test description

7.5.1 Type of tests/Problems that can be explored

The GeoModel container can be used for studying soil behavior and the interaction with structures, with accurately prepared sand and clay models. Research areas normally supported by the infrastructure are geotechnics, soil mechanics and soil structure interaction for i.e. dike & dam construction, tunneling and pipelines, among others. Recent studies in the GeoModel container have provided insights into the deformations of underground utilities, effectiveness of mitigating measures for piping (internal erosion) of flood defenses and validation tests for domestic gas pipe connection in settling soil.

7.5.2 Material suitable for the tests

The model container can be filled with granular material and/or clay. It is possible to insert constructions in the container to examine the soil/construction interaction. Since the model container is a versatile and generic facility it is virtually useable for any soil mechanical experiment.

7.5.3 Test system limitations and constraints

- Test set-ups will not be installed before approval by Deltares staff
- Tests will not be performed without Deltares staff
- All test set-ups should be designed to perform within the parameters of the model container
- Test will not be performed with materials that can cause hazards for health and/or environments

7.6 Examples of results

Some examples of tests at the GeoModel container are given in Table 20.

Table 20 Examples of tests at the Deltares GeoModel container

A. Validation tests for domestic gas pipe connection in settling soil	
 1. Filling of the model container with the testing sand	 2. Installation in the model container of the gas pipe and its connection mounted on a vertical frame
 3. Finilizing the testing set-up	 4. Simulation of ground settlement by moving the vertical wall upwaards (20 cm settlement)
 5. Simulation of ground settlement by moving the vertical wall upwaards (80 cm settlement)	 6. Gas detection measurements were taken during testing
7. The force applied on the connection of the gas pipe with the wall and the deformation of the gas pipe was measured for each ground settlement step	

B. Monitoring of deformation of underground pipes

1. Placement of the pile in the model container. The diameter of the HDPE pipe was 50 mm with a wall thickness of 4.6 mm. The pipeline was laid 200 mm below ground level and at 150 mm from a sheet pile wall.

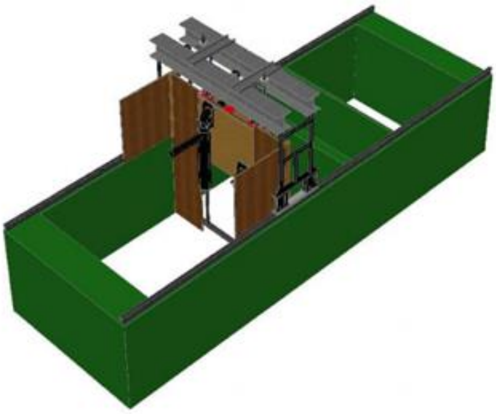
2. Sand has been carefully applied on top of the pipe. Before the start of the trial, a homogeneous loosely packed sand was prepared. This is done by fluidizing the sand (flowing upwards by means of water supplied from underneath over the entire bottom). In this way a sand package with a relative density of approximately 25% is obtained. The vertical and horizontal displacement of the ground was measured using Shape Accel Array Filed sensors.

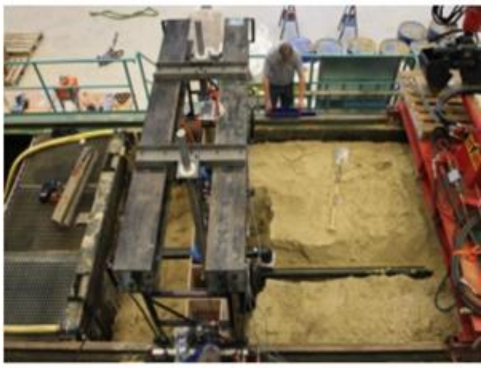
3. The sheet pile wall (l 90 w 60 x d 1 cm) was vibrated into the sand package in the center of the model container for a few minutes at a speed of 3 mm / s (30 Hz).

4. The soil deformation and pipe displacement before the sheet pile wall vibrates (initial situation), after the sheet pile wall has been vibrated in (sheet pile at deepest point) and after the sheet pile wall has been pulled out again was measured

7.7 Relevant projects performed in the facility

A brief overview of projects performed at the GeoModel container is given in what follows.





Project title: Tests on sinking ground structures (Test op zakkende grondconstructies)

Client: Pipelife (https://www.pipelife.nl/)

Project Objective: Assessment of the performance of sinking ground structures as a measure for improving the safety of the Dutch gas network. Large parts of The Netherlands suffer from subsidence. As the ground settles the buildup of pressure on the infrastructure of all pipes is increasing which can lead to breakage of the pipes which can be a life-threatening situation for the case for the case of gas pipes. To prevent breakage from occurring a new solution has been designed at tested in the Geo ModelContainer (sinking ground structure, "zakkende grondconstructie, ZGC). Testing has been performed to evaluate whether the proposed solution fulfils the required regulations/requirements. For the testing a sand package has been build up in the model container with a relative density between 50 – 70%. A foundation beam with the ZGC structure mounted with a gas pipe is pulled vertically at a constant speed for simulating the action of ground subsidence.

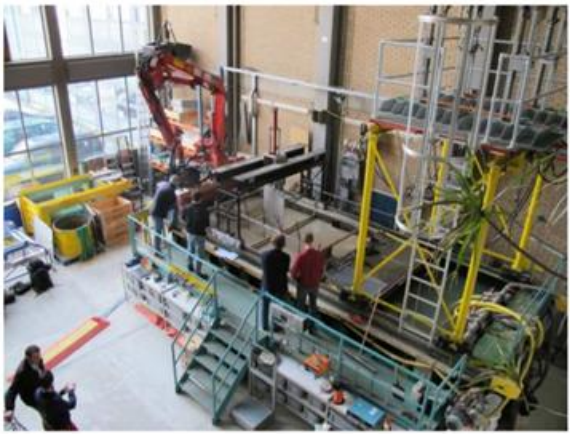
Measurements/Instrumentation:

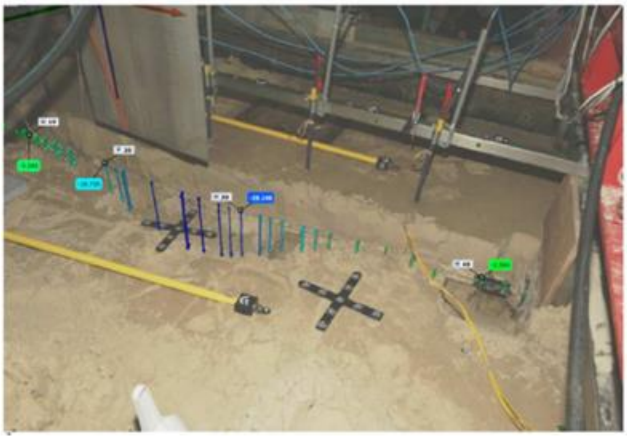
- Displacement of the ZGC structure (displacement sensors, range of 850 mm, accuracy of 0.1 mm)
- Displacement of the gas pipe (DLE Laser Plus, measurement accuracy of 3 mm)
- Vertical force on the ZGC structure (S9M HBM sensors with a calibrated range of 2 kN, measurement accuracy of max 0.25%).
- Gas tightness (Druck Limited pressure transducer – model PDCR10, calibrated range of 100 kPa, measurement accuracy of 0.1%).

Deliverables:

1. M. P. Harkes (2014). "Test op zakkende grondconstructie." Deltares report. 1208409-003-GEO-0002. In Dutch.
2. https://www.pipelife.nl/content/dam/pipelife/netherlands/marketing/infrastructure/gas/pdf/Zakkende%20Grondconstructie%20groot%20brochure_LR.pdf

Contact person: For additional information please contact marien.harkes@deltares.nl or paul.schaminee@deltares.nl





Project title: Sensor Technology Applied To Underground Pipelines (Sensortechnologie Toegepast Op Ondergrondse Pijpleidingen)

Client: TNO (https://www.tno.nl/nl/)

Project Objective: Validation of the concept of monitoring underground pipelines in the gas distribution network. The overall objective is the reduction of uncertainty concerning the probability of failure of the pipes. Uncertainty can be reduced via application of sensors which can, for example, provide information on ground movement. Validation experiments have been performed in the Geo ModelContainer. In these experiments two types of monitoring sensors were used: (i) Shape Accel Array Filed (SAAF) and (ii) photographic sensors. For the tests a pipe with a diameter of 50 mm and a wall thickness of 4.6 mm was placed in the middle of the container. Different set-ups were applied for simulating different case scenarios (compaction, top load and excavation).

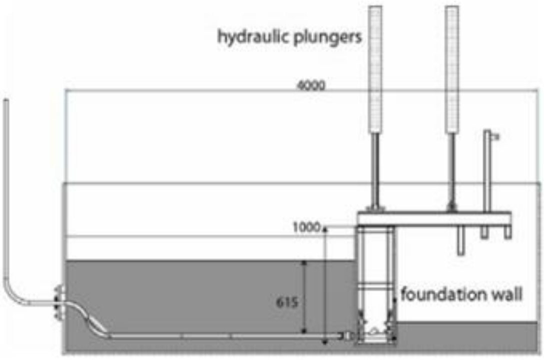
Measurements/Instrumentation:

- Stretch of the pipe (Fiber Bragg Grating, FBG, technology)
- Displacement of the ground in vertical and horizontal direction using SAAFs
- Vertical positioning of the pipe (manual laser measurements)
- Vertical and horizontal positioning of the pipe using a photographic technique

Deliverables:

1. Courage et al. (2013). “Sensortechnologie Toegepast Op Ondergrondse Pijpleidingen – Fase 2.” TNO report. TNO 2013 R12127, versie 2.1.
2. https://www.youtube.com/channel/UC1uY-Sj1knzYAczfW8vHsyQ

Contact person: For additional information please contact marien.harkes@deltares.nl or henk.kruse@deltares.nl



Project title: Testing gas pipes in settling soil (Gasleidingen in zakkende grond)

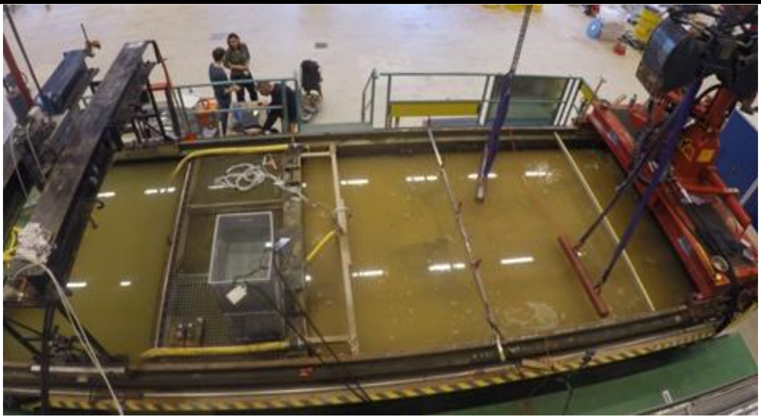
Client: ENECO (https://www.eneco.nl/)

Project Objective: In 2003 Dutch gas suppliers initiated a research project to gain a better understanding of the relevant mechanisms involved with service pipe connections in settling soil. For this, full-scale models of house connections for gas pipes were built under laboratory conditions in the GeoModel Container. Based on the results of a first test series with a number of existing solutions new ideas were developed to optimize the connection. To simulate worst-case conditions the GeoModel container was filled with model sand that was compacted to a relative density of 40 to 50%. For the same reason the water table was lowered almost to the bottom of the container. This created unsaturated conditions with capillary forces. For such conditions the resistance of the sand was at maximum. The differential settlement of the pipe was enforced by pulling the system with two plungers, thus simulating same forces and displacements as would be the case for settling soil.

Measurements/Instrumentation:
- Force transducers to measure the forces at the connection point of the pipe with the gas meter
- Vertical displacement of the pipe measured with a laser equipment

Deliverables:
1. Bezuijen A., Viehofer, T. (2003). “Gasleidingen in zakkende grond.” GeoDelft report. C0-407260.0019v2. In Dutch
2. Bezuijen A., Viehofer, T. (2006). “Testing service pipes in settling soil.” Proceedings of the Sixth International Conference on Physical Modelling in Geotechnics, 6th ICPMG '06, Hong Kong, 4 - 6 August 2006.
https://www.youtube.com/channel/UC1uY-Sj1knzYAczfW8vHsyQ

Contact person: For additional information please contact Adam.Bezuijen@deltares.nl or paul.schaminee@deltares.nl




Project title: Pipe uplift in liquefied sands

Client: Master thesis

Project Objective: Induced earthquakes in the Groningen area in The Netherlands are becoming heavier which was the main reason to investigate the effect on pipelines. According to previous investigations conducted by Deltares liquefaction can occur during future induced earthquakes. Liquefaction can cause pipe uplift and therefore differential displacements, for instance at a pipe-structure connections. This causes stresses in pipelines and the possibility of pipe failure with all consequences of such. For creating a model for the pipe uplift in liquefied sands, experiments were performed at the GeoModelContainer with the objective to determine (a) the liquefaction time and (b) the resistance against pipe uplift. For the experiments a thick full saturated loose sand layer was build-up. Liquefaction was caused by the impact of a falling weight on the sidewall of the sand container.

Measurements/Instrumentation:

- Pore water pressure transducers
- Displacement gauges
- Strain gauges

Deliverables:

1 Horsten, T. (2016). "Pipe uplift in liquefied sands. The case of induced earthquakes in the Groningen area." Master thesis. Delft University of Technology. Section of Geo-Engineering

2. https://www.youtube.com/channel/UC1uY-Sj1knzYAczfW8vHsyQ

Contact person: For additional information please contact henk.kruse@deltares.nl

7.8 Reference papers

1- Bezuijen A., Viehofer, T. (2006). "Testing service pipes in settling soil." Proceedings of the Sixth International Conference on Physical Modelling in Geotechnics, 6th ICPMG '06, Hong Kong, 4 - 6 August 2006.

2- Horsten, T. (2016). "Pipe uplift in liquefied sands. The case of induced earthquakes in the Groningen area." Master thesis. Delft University of Technology. Section of Geo-Engineering.

8 Geo-Centrifuge (DELTARES)

8.1 Basic information

Table 21 collects some basic information about the facility.

Table 21 Basic information of the Geo-Centrifuge facility (Deltares)

Geo-Centrifuge	
Name (short)	Geo-Centrifuge
Name (long)	Geo-Centrifuge
Owner	Stichting Deltares
Location (City/Country)	Delft/The Netherlands
Address	Boussinesqweg 1, 2600 MH, Delft, The Netherlands
Website (vernacular language)	https://www.deltares.nl/en/facilities/geocentrifuge/
Website (English)	https://www.deltares.nl/en/facilities/geocentrifuge/
Contact (e-mail)	Rob.Zwaan@deltares.nl ; Jarno.Terwindt@deltares.nl
Head of facility (name/e-mail)	Harm Aantjes / Harm.Aantjes@deltares.nl
Construction year	2020 (operational in 2021)

8.2 Scope of the facility

The Geo-Centrifuge is used for testing physical scale models of geotechnical engineering systems such as natural and manmade slopes, earth retaining structures and foundations. By increasing earth gravity, real stresses can be scaled down to models and for natural processes in soil time can be accelerated and brought back from decades to hours. The Geo-Centrifuge can be used for scientific research in the energy, urban, water and transport infrastructure sector and in validating applied models.

8.3 Facility physical description / Technical specifications

8.3.1 Specifications

The Deltares Geo-Centrifuge is a C72-3 beam type centrifuge manufactured by Actidyn. It has a 260 g-ton capacity and a platform radius of 5.0 m. The platform can house test set-ups with dimensions up to 1.2 m x 1.2 m x 1.8 m (length x width x height). The Geo-Centrifuge has the following specifications:

- Platform radius 5 meter
- Basket 1,2 x 1,2 x 1,8m
- Maximum payload 2600kg at 100g
- 1400kg at 130g
- 1000kg at 150g
- Max speed 180rpm / 340km/h
- Power consumption max 280kW
- Operation at atmospheric pressure
- Automatic imbalance detection
- Water, air and hydraulic slip rings
- Electric and fiber-optic slip rings

- 2 x 19” rack on top of GeoCentrifuge
- Complete surveillance of centrifuge parameters
- Remote controlled operation possible
- Suited for later addition of an earthquake simulator

The Deltares Geo-Centrifuge is designed to make later installation of an earthquake simulator possible. For this purpose, the centrifuge is equipped with an earthquake simulator prepared reinforced platform and an extra set of high-pressure hydraulic sliprings to power the simulator.

It should be pointed out that the C72-3 type of the centrifuge at Deltares is for a large part comparable with the centrifuge delivered to the Center for Offshore Foundation systems at the University of Western Australia (Gaudin et al., 2018) and the Korea Advanced Institute of Science and Technology (Kim et al., 2006).

Photos of the Deltares Geo-Centrifuge are shown in Figure 58.

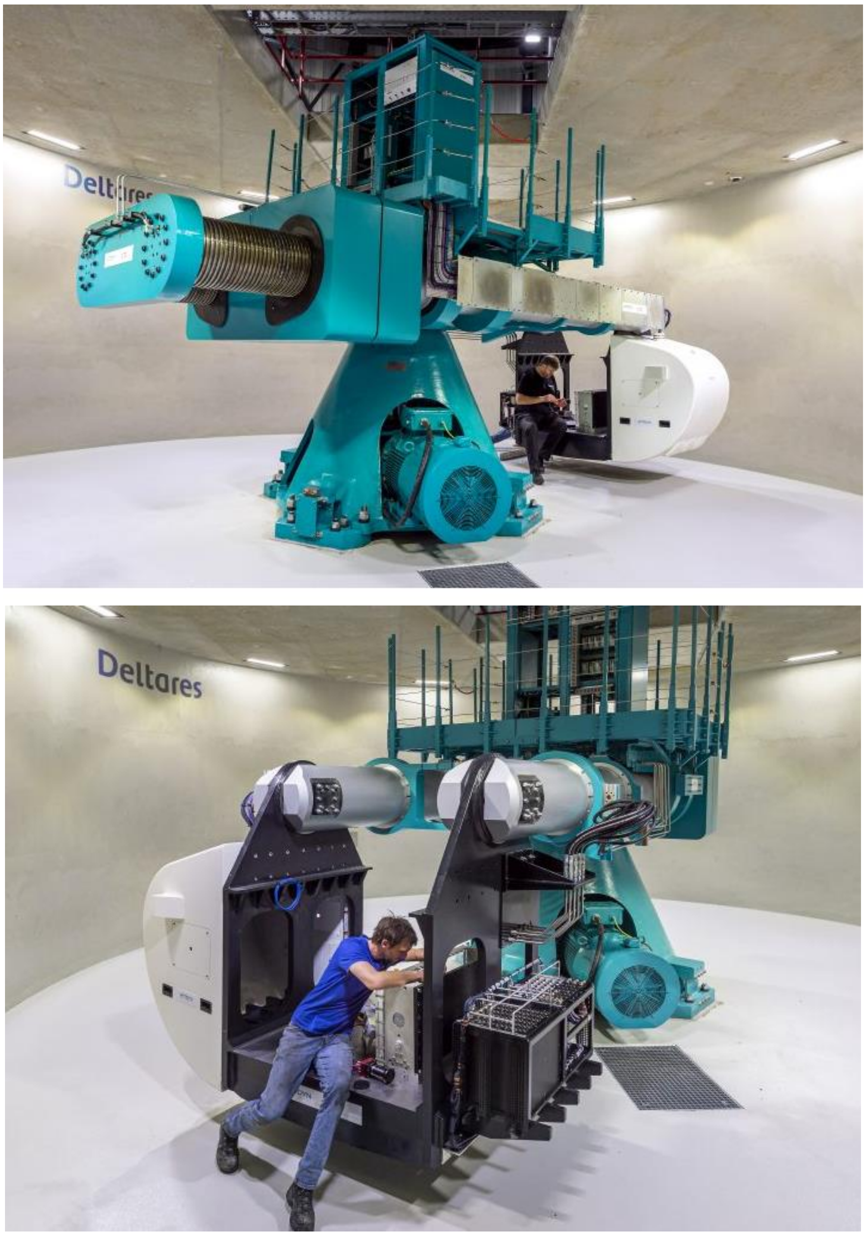


Figure 58 The Deltares geotechnical centrifuge

8.3.2 Centrifuge systems

The Geo-Centrifuge is equipped with several systems necessary to perform experiments. A description of these systems is given in what follows.

Test control system

The test control system is designed to perform any remote action that could be needed during centrifuge experiments. The system is completely designed and built by Deltares and uses CompactRIO hardware and software from National Instruments. The CompactRIO system consists of a controller with a processor and user-programmable FPGA (fieldprogrammable gate array) that is equipped with conditioned I/O modules. The communication is mainly done over ethernet and fiber-optic cables and sliprings, but partially the I/O ports are also copper wired over the signal slip rings to terminations in the 19” rack in the centrifuge control room for extra flexibillity. The software user interface enables full control of the whole system from the control room.

Data acquisition system

For the data acquisition system HBM QuantumX modules are chosen in combination with CatMan AP software. The data-acquisition hardware is divided into a system in the control room and a system in the centrifuge basket and rotor 19” cabinet. The system consists of a BPX002 19” backplane at each location that can houses the several available QuantumX modules such as the MX840B 8 channel high-dynamic universal amplifiers, the MX879B analog/digital I/O modules, the CX27C ethernet gateway and the MX410B 4-channel high-dynamic universal amplifiers. The MX410B can handle data rates up to 100 kS/s (maximum 38 kHz signal bandwidth) and the MX840B can handle 40kS/s (maximum 7.2 kHz signal bandwidth). The MX879B module provides 8 real-time math possibilities, output of calculated input signals, signal generator features and 32 digital I/O ports. The CX27C module provides 1 Gb/s transmission and PTP (Precision Time Protocol) functionality for the modules in the backplane. The systems are connected to each other and the control room over ethernet and fiber optic cables and rotary joint. The modular system ensures very flexible addition of extra modules for data-acquisition purposes and easy maintenance or repair work. The CatMan AP software ensures easy set-up of data-acquisition sessions, flexible real-time monitoring during tests and extensive data processing possibilities.

Video acquisition system

The centrifuge is equipped with 4 FLARE 48M30CCX cameras with a resolution of 7920 x 6004. These cameras can be monitored real-time on the dedicated control PC in the control room of the centrifuge while the images are stored on 2 DVR systems in the control room for later analysis purposes. 2 High-speed cameras AOS LVIT-2500 are also added to the centrifuge for capturing i.e. events during dynamic experiments. The images from these high-speed cameras cause a data stream (2500fps at 2Mp) that is way too large to transmit, so the images are stored inside the camera on a memory card. Due to the enormous amount of data the record time is limited to 4 seconds on highest frame rate and resolution, larger record time can be obtained by decreasing frame rate and/or resolution. After the experiment is finished the images are downloaded to the dedicated control PC for further analysis. Besides the cameras for video acquisition, the centrifuge has two additional fixed onboard cameras to monitor the centrifuge itself. One camera overlooks the whole centrifuge basket and the other camera is pointed at the 4-D robotic system. The images can be monitored (and/or recorded) in the control room on a separate screen.

4-D Robotic system

The centrifuge is equipped with a 4-D robotic system (supplied by Actidyn). This system provides actuator and tool flexibility during flight up to a g-level of 100 g. The 4-D robot creates the possibility to use 4 different tools on any location covering almost the whole surface of the centrifuge basket during flight. The system is placed on brackets on the centrifuge container side walls at a height of 1.2 m from the floor of the basket. The system is fitted with two perpendicular electric displacement axes in a plane parallel to the bottom of the centrifuge basket and a dual electric axis of displacement and/or rotation perpendicular to the previous mentioned plane. The axis can be used to maneuver tools and are able to produce a force of up to 5 kN, a torque of up to 5 N·m and a speed of up to 50 mm/s with a positioning accuracy within 1 mm on each axis and 1° on the rotation axis. The tool holder can move along all four axes simultaneously and can pick up or place back the different available tools during flight enabling flexible use of different functionalities.

8.3.3 Geo-Centrifuge utilities

For the centrifuge a number of utilities are available to facilitate soil model preparation and testing. A description of these utilities is given in what follows.

Clay slurry mixer

The clay mixer is manufactured by Heilig BV from Heerhugowaard (NL) and is delivered completely with the steel construction and platform giving access to the top of the mixer. The mixer has a work volume of 500 l, can handle grains up to 3 mm and can be vacuumed down to 50 mbar(a) in order to create a slurry that is free of air bubbles. The conical mixer has a sanitary open mixing screw to avoid lump formation while mixing and is provided with a CIP (clean-in-place) system that ensures easy and thorough cleaning after use. The outlet of the mixer on the bottom is provided with a ball valve and a flange of 125 cm diameter. Below this flange, a table with a hydraulic jack can be placed. A clay consolidation cell can be placed on top of this table. The hydraulic jack function pushes the consolidation cell firmly to the flange ensuring an airtight connection. After this, the consolidation cell can be vacuumed to the same pressure level as inside the clay mixer. In this way the air free slurry from the clay mixer will flow air free into the consolidation cell when the ball valve is opened. Then the consolidation cell can slowly be brought to atmospheric pressure again and installed into the consolidation frame.

Consolidation frame

To consolidate the clay slurries from the clay mixer the consolidation frame can be used. This frame consists of a highly reinforced and stiff frame, a hydraulic actuator with a stroke of 1.5 m, a hydraulic power supply up to 15 MPa and a control system. The frame can be used for uniform consolidation or a depth variable consolidation based on the hydraulic gradient method. During consolidation, parameters such as pressure, flow, temperature, are independently controlled and monitored. The control system also incorporates safety circuitry that are essential to the safe operation of the system. After the user has programmed the desired consolidation path, the system operates fully automatic until consolidation is finished. Besides the option of using this consolidation frame, it is also possible to consolidate samples during flight using the increased g-force of the centrifuge.

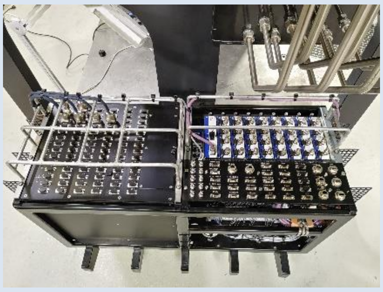
Sand rainer

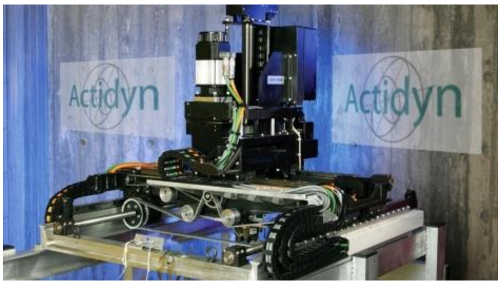
For the preparation of sand models an Actidyn, an on-the ground sand-rainer (sand hopper) will become available in 2021. This sand rainer allows the preparation of homogeneous sand beds of a chosen density. With its controlled constant flow and a constant height of fall, its entirely automatic horizontal and vertical movement commands, models of near-perfect uniformity across the entire volume of the container can be produced. With an appropriate choice of sand flow and falling height it is possible to obtain a variety of densities, from loose to very dense. The hopper translation displacement is supported and guided by two rails that are supported be a steel frame. The hopper height is controlled by a lift mechanism consisting of two steel cable roller drums driven by a variable speed motor gear controller. The system is fully automated.

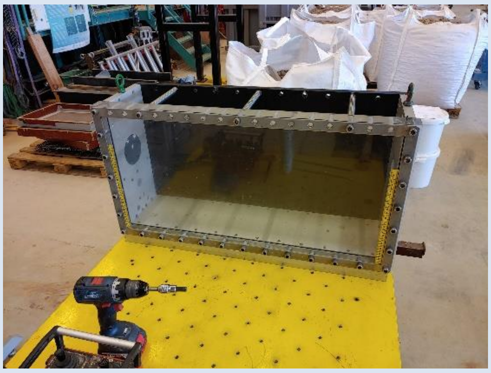
8.3.4 Overview of systems/utilities/equipments

An overview of the available centrifuge systems, utilities and equipment together with a brief description of their technical specifications is given in Table 22.

Table 22 Overview of systems/utilities/equipment of the Deltares geo-centrifugeExisting

Systems/utilities/equipment	Photo	Description
Test control system		- 2 compactRio systems (one in the 19'' racks and one in the centrifuge test basket) - Wide range of I/O ports - (Adjustable) power supplies - Lighting control - Analog/Digital I/O connections - Software user interface - Hydraulic plunger control - Camera connections - Ethernet/USB connections
Data-acquisition system (supplied by HBM)		- HBM quantum MX840B, MX879B, MX878B, MX410B and CX27C modules available. - 3 19" backplanes available at control room, rotor and basket for easy installing of modules. - Sensor identification and configuration - Proven reliability in several centrifuges worldwide - Can handle 17 different transducer techniques - CatMan AP Daq-software
High speed cameras (manufactured by AOS Technologies AG)		- AOS L-VIT 2500 - 2 MP resolution - 2500 fps frame rate for a period of 5s
Monitoring cameras (manufactured by Flir Systems Inc.)		- 4 FLARE 48M30CCX cameras - 7920 x 6004 resolution - 26 fps frame rate
Fixed on-board cameras		- Resolution of 5 MP - 26 fps frame rate

Systems/utilities/equipment	Photo	Description
4D Robotic system (manufactured by Actidyn)		The 4-axis robotic system allows in-flight excavation and installation operations. - In-flight pick-up and operation of up to 4 different tools - x, y, z movement and 360o rotation of tools - Operational up to100g - Force application up to 5Kn - Torque application up to 5N.m - Displacement up to 5cm/s - Accuracy 1mm per axis - Accuracy rotation 1o - Completely programmable - “Safe-zone” addition possible - Universal tool holder
Clay slurry mixer (supplied by Heilig BV)		- 500 liter capacity conical mixer - Vacuüm mixing capability - Disposing to model container in vacuum
Clay consolidation frame (by Actidyn)		- Stand-alone consolidation system - Uniform consolidation up to 0,2MPa - Programmable consolidation steps - Suited for circular and rectangular containers - Plunger stroke 1,5m

Systems/utilities/equipment	Photo	Description
Strongboxes		- Structurally reinforced to minimize mechanical deformation during flight - Can be used as consolidation cells - Cylindrical strongboxes available in 30/60/90 cm internal diameter; can be stacked up to the desired height - Rectangular strongbox available of 80 cm x 20 cm x 40 cm (l x w x h) with one transparent wall - Drainage system at the bottom - Feed-through options in the bottom and walls for water and/or air hoses and possibility for entry of sensor cables
Sand rainer (by Actidyn)		- Sandhopper width, depth and height of 1050, 430 and 550 mm respectively. - Sandhopper usable volume of 0.14 m3 - Sand weight of 245 kg, empty mass of 45 kg. - Horizontal motion with displacement range of 0 – 2000 mm, command resolution of 0.1 mm, linear speed of 1 – 15 m/min and rate resolution of 0.1 m/min. - Vertical motion with displacement range of 0 – 2000 mm, command resolution of 0.1 mm, linear speed of 0.2 – 1.2 m/min and rate resolution of 0.01 m/min.

8.4 Sensors and instrumentation used in the facility

For centrifuge testing, a wide and common range of sensors is available. Table 23 provides an overview of the latest additions on miniature sensors. All sensors can be calibrated in-house and are traceable to (inter)national standards.

Table 23 Sensor and instrumentation of Geo-Centrifuge

Physical magnitude to be measured	Type of sensor	Description	Range measurement	Accuracy
Pore pressure	Pore pressure transducer	MEAS France EPB-PW-7BS/Z0/PC0.5/L5M	0-700kPa	0,5%FS
Displacement	Laser	ODS black-line	Several ranges	0,05mm
Soil Pressure	Soil pressure	KYOWA BEC-A-1MP	1MPa	2%FS
Force	Force transducers	HBM U9C	Several ranges	Class 0,2

In addition, for the centrifuge experiments a variety of additional equipment are available such as:

- Hydraulic 50 kN hydraulic actuators with strokes of 10 cm up to 70 cm
- Hydraulic and electric pumps
- Pneumatic and electric valves

- Penetrometers in several diameters, lengths, fitted with or without T-Bar and/or pore pressure transducers.

8.5 Test description

8.5.1 Type of tests/Problems that can be explored

Raising gravitational forces in the Geo-Centrifuge allows (i) scaling down the geotechnical processes and (ii) the simulation of them on scale. In addition, time is accelerated. Consequently, physical processes in the subsoil that would normally take several years can be reduced to a few hours. That makes it possible to test structures in the subsoil that have never been built before, such as tunnels or dikes. Examples of problems that be explored in the centrifuge are:

1. Wind turbines are getting bigger in the near future. In the North Sea, they will be about 300 m tall already within a few years. Such large turbines have never been built and that has implications for design and construction. Deltares shall use the centrifuge to test and validate the foundations of the turbines.

2. Dikes have to be safe. The Geo-Centrifuge shall be used to subject dikes to conditions that can occur, but hardly ever seen in real life, such as extreme high-water levels or drought.

3. The infrastructures in the water, energy, urban transport, and goods transport sectors is facing major challenges: from the effects of extreme weather to ageing and more intensive use. The Geo-Centrifuge shall be used to simulate the effects on both existing and new infrastructure.

As described in Section 8.2, the set-up and available utilities/instrumentation make a wide range of tests possible.

8.5.2 Material suitable for the tests

The Deltares Geo-Centrifuge is focussed on soft soil behaviour. As aforementioned, for the centrifuge, several utilities are available to facilitate soil model preparation using different type of soils (both cohesive and cohesionless soils). For the preparation of **clay** samples, the clay slurry mixer and the consolidation frame can be used. The preparation of a slurry by mixing clay and water under vacuum and subsequent consolidation of the mix to a designated pressure, allows the preparation of a homogeneous clay model for centrifuge testing with accurately defined geotechnical characteristics. The preparation of homogeneous **sand** soil models at a chosen relative density can be achieved with the on-the-ground sand-rainer. By adjusting the sand flow and falling height of the rainer, sand densities varying from loose to very dense can be achieved.

It should also be pointed out herein that Deltares has experience with the preparation of soil models for centrifuge testing for which viscous pore fluid can be prepared at the desired viscosity.

8.5.3 Test system limitations and constraints

- The test set-up cannot be larger than the centrifuge container
- The complete test set-up should be able to withstand the gravitational force during tests
- All actions to be performed during test should be done by remote control
- Test set-ups will not be installed before approval by Deltares staff
- Tests will not be performed without Deltares staff
- All test set-ups should be designed to perform within the design parameters of the Geo-Centrifuge
- Test will not be performed with materials that can cause hazards for health and/or environments

8.6 Examples of results

The Deltares geo-centrifuge will be operation after the 2nd semester of 2021. Examples of test results are thus not available at the time being.

8.7 Relevant projects performed in the facility

The geocentrifuge is expected to be operational in 2021. To this end, there is not yet a record of projects that have performed at this infrastructure. Geocentrifuge tests are, however, already planned for the 3rd and 4th quarter of 2021 and the years thereafter. Reference to projects for which the facility is scheduled to be used is provided in what follows.

Project title: Sustainable and low-cost installation of monopile foundations for future very large wind turbines

Client: Joint Industry Project (JIP) funded by Netherlands Enterprise Agency, RVO and other industrial companies and research institutes in The Netherlands.

Project objective: In order to study the drivability aspects and lateral bearing capacity response of the soil to the different installation techniques the Deltares state-of-the-art GeoCentrifuge will be used. The objective is to compliment the field-testing program by closing any gaps and generating additional and necessary data sets that are required for model development and validation. The Deltares GeoCentrifuge offers the option for reproducing meaningful stress levels in the soil through the augmented gravity induced by sample spinning. Different combinations of soil conditions, pile geometry, pore-water drainage will be considered, with emphasis on scenarios relevant to North Sea conditions.

Project period: 2021 - 2026

Contact person: Ahmed.Elkadi@deltares.nl

Project title: MIDAS: Monopile Improved Design through Advanced cyclic Soil modelling

Client: Joint Industry Project (JIP) funded by Netherlands Enterprise Agency, RVO and other industrial companies and research institutes in The Netherlands.

Project objective: MIDAS' experimental programme will be conducted at TU Delft and Deltares using two different centrifuge facilities with the aim of (i) investigating the mechanics of monopile-sand interaction, and (ii) producing novel data in support of numerical modelling and, ultimately, monopile design. During centrifuge experiments, a model which is geometrically N times smaller than the real prototype will be tested under enhanced acceleration – N times the Earth's gravity. This allows to re-establish appropriate stress levels and obtain reliable test results, on condition that proper scaling laws and boundary conditions are

	fulfilled. Having access to two set-ups with different scales provides the unique possibility to test the concept of modelling of models for the case of MPs subjected to lateral cyclic loading. **Project period:** 2020 - 2024 **Contact person:** Ahmed.Elkadi@deltares.nl

8.8 Reference papers

1- Zwaan, R., Terwindt, J., deLange, D., Bezuijen, A. (2020). "A new centrifuge at Deltares, Delft, The Netherlands." Proceedings of the 4th European Conference on Physical Modelling in Geotechnics, 7-8 Sep, 75-83, Laue & Bansal (eds.)

2- Terwindt J., van der Star W., de Lange, D. (2020). "Carboxymethylcellulose as a Newtonian viscous fluid for centrifuge modelling." Proceedings of the 4th European Conference on Physical Modelling in Geotechnics, 7-8 Sep, 75-83, Laue & Bansal (eds.)

8.9 Other relevant information

Deltares has a 30 years' experience on centrifuge testing. From 1987 until 2017 Deltares has been operating a geotechnical centrifuge for research on soil mechanics. That centrifuge had a beam of 6 m, a payload capacity of 1050 g-tonne, a basket size of 2 m x 1 m x 1 m (l x w x h) and could only operate under vacuum. The centrifuge contributed to a large amount of geotechnical research projects among which:

- Validation of calculation methods for dike stability
- Pile-tunnel interaction for construction of TBM tunnels
- Influence of ship impact on bridge foundations in Hong Kong and Incheon
- Pile capacity, rapid pile load testing, pile group effects
- Offshore projects; jack-up-seabed interaction, dragging of anchors

9 Schofield Centre (UCAM)

9.1 Basic information

Table 24 provides some basic information about the facility.

Table 24 Basic information of Schofield Centre

Schofield Center for Geotechnical Process and Construction Modelling	
Name (short)	Schofield Centre
Name (long)	Schofield Centre for Geotechnical Process and Construction Modelling
Owner	University of Cambridge
Location (City/Country)	Cambridge, UK
Address	High Cross, Madingley Road, Cambridge, CB3 0EF
Website (vernacular language)	https://www-geo.eng.cam.ac.uk
Website (English)	https://www-geo.eng.cam.ac.uk
Contact (e-mail)	Prof. Giulia Viggiani: gv278@cam.ac.uk
Head of facility (name/e-mail)	Prof. Gopal Madabhushi: mspg1@cam.ac.uk
Construction year	Extended and rebuilt in 2002

9.2 Scope of the facility

The Schofield Centre for Geotechnical Process and Construction Modelling hosts equipment to facilitate physical modelling of geotechnical systems such as , shallow and piled foundations, open excavations and tunnels, engineered slopes, and retaining structures under complex loading including mechanical, seismic, hydraulic, and thermal actions. Reduced scale models tested at increased gravity ensure stress similarity between homologous points in the model and in the prototype and permit to speed up all processes driven by transient consolidation associated with migration of pore water down gradients of pore water head. In a centrifuge model constructed at a linear scale of 1/N and tested at N*g* consolidation time scales as $1/N^2$; if N=100, less than one hour of model time represent one year of prototype time, making it possible to simulate, *e.g.*, weather cycles and seasonal variation of boundary conditions on a slope in feasible testing times.

9.3 Facility physical description / Technical specifications

The Schofield Centre hosts two major facilities:

1. The Turner beam centrifuge

- Manufacturer: Cambridge University Engineering Department
- Year first used: 1972
- Radius to base of soil container (m): 4.125
- Max size of soil sample (m^3) L×W×H: 0. 855×0. 855×1.50
- Bucket area (m^2): 0.855
- Max Design Acceleration (g): 150
- Max Design Carrying Capacity (ton): 1
- Max Acceleration used (g): 150 carrying (ton): 1
- Max Load Tested (ton): 1 at (g): 150

2. The MKII minidrum centrifuge

- Manufacturer: Department of Engineering, Cambridge (ANS&A)
- Year first used: 1995
- Radius to base of soil container (mm): 370
- Max size of soil sample (m3) L×W×H=2.13×0.18×0.12
- Max Design Acc (g): 470

The 10 m diameter and 150 g-tonne Turner beam centrifuge, see Figure 59(a) is the focus of centrifuge based geotechnical modelling at Cambridge. The beam centrifuge was built in the early 1970s to designs by Philip Turner, described here. The large capacity of this centrifuge together with its physical size give great scope for the building of novel experimental packages. Electrical and hydraulic slip rings are available for the passing of water, compressed air and power to packages, enabling to construct and use complex actuators. A large number of experiments have been carried out and a great deal of experience has been accumulated over the past 40 years, enabling modelling of such diverse situations as earthquake loading and climatic fluctuations. Present PhD projects include earthquake loading of geotechnical and structural systems, monopile foundations for offshore wind, piled foundations under complex loading, tunnelling and retaining walls.

A successor to the earlier Cambridge MKI minidrum centrifuge (now at Horoshima University), the 0.8 m diameter twin-shaft MKII minidrum centrifuge, see Figure 59(b), was developed in the mid-1990s to provide a relatively inexpensive and quick alternative to conventional larger-scale centrifuge model tests. With its small radius, the minidrum centrifuge is ideally suited to teaching applications and the modelling of processes where large quantities of soil are expensive to retrieve (*e.g.*, seabed pipelines). At a 1/400 scale, a prototype site of dimensions L×W×H=850×70×50 m^3 can be modelled in the ring channel. A particular feature of the Cambridge drum centrifuges, pioneered by Andrew Schofield, is their twin coaxial shafts - they are, effectively, one centrifuge (the central turntable, carrying actuators or tools) rotating independently of the other (the ring channel, carrying the soil). This makes it possible to keep the soil spinning correctly, while carrying out the various stages of model preparation and actuator interventions in sequence by stopping and starting the central turntable. A feature (covered by a patent application) of both the MKI and MKII minidrum centrifuges is the ability to rotate the drum through ninety degrees without stopping the spinning drum. This allows soil and water to be added into the channel with the axis horizontal and subsequent model testing carried out with the axis vertical to eliminate the +/-1g variation in accelerations, see Barker, 1998.

Both centrifuges have fibre-optic communications and are equipped with several systems to perform experiments.

For the Turner beam centrifuge, data acquisition is carried out using on-board computers. It is possible to log up to 60 channels in any given test at a sampling frequency of 10 kHz. Two high-speed cameras are available to obtain high resolution images for Particle Image Velocimetry:

- 1.3 megapixel MotionBlitz Cube2 500 fps GigE high-speed monochrome camera; link
- 12 megapixel DaHeng Imaging MARS-1231 32 fps USB 3.0 monochrome camera; link

Raspberry Pi imaging systems have also been developed for use on both centrifuges, see Eichhorn *et al*. (2020)

Different containers (Figure 60) are available to house soil models including:

- cylindrical tubs with a diameter of 850 mm;
- several windowed strongboxes for PIV of varying size;
- several Equivalent Shear Beam (ESB) centrifuge strongboxes for earthquake testing (Madabhushi *et al*. 1998);
- laminar centrifuge strongbox for earthquake testing (Reference, YEAR);
- *ad-hoc* containers designed and built for specific projects.

Quasi-static actuation systems include:

- 1×10 kN 2D actuator with 500 mm horizontal travel and 300 mm vertical travel and 5 mm/s maximum displacement rate, see Figure 61(a) (Haigh *et al*., 2010);
- 1×10 kN kN 1D actuator with 300 mm vertical travel and 5 mm/s maximum displacement rate, see Figure 61(b);
- A range of electric linear actuators with capacities of 0.5-4.7 kN and strokes of 100-300 mm.

Two dynamic actuators are currently used on the Turner beam centrifuge, namely the Stored Angular Momentum (SAM) actuator (Madabhushi *et al*., 1998), purely mechanical, and the more recently added Servo-Hydraulic earthquake actuator (Madabhushi *et al*., 2012). The SAM actuator, see Figure 62(a), can apply powerful sinusoidal shaking motions at *g* levels of up to 100*g*. The peak dynamic force that this actuator can produce is about 100 kN. The Servo-hydraulic earthquake actuator, see Figure 62(b), can apply realistic acceleration time histories mimicking real earthquakes and can operate at *g* levels of up to 80*g*. This actuator can produce a dynamic force of 100 kN and operate in the frequency range of 10-200 Hz.

A number of utilities are available to prepare clay and sand soil models, as follows:

- 1 clay mixer, see Figure 63
- 2×500 kN hydraulic presses for clay sample consolidation, see Figure 64(a);
- 1×250 MN pneumatic press for clay sample consolidation, see Figure 64(b);
- A fully-automated 3-axis sand pourer, see Figure 65 (Zhao *et al*., 2006);
- CAM-SAT back-saturation apparatus, see Figure 66 (Stringer *et al*., 2009).


(a)


(b)

Figure 59 Schofield Centre geotechnical facilities: (a) Turner beam centrifuge; (b) MKII minidrum centrifuge

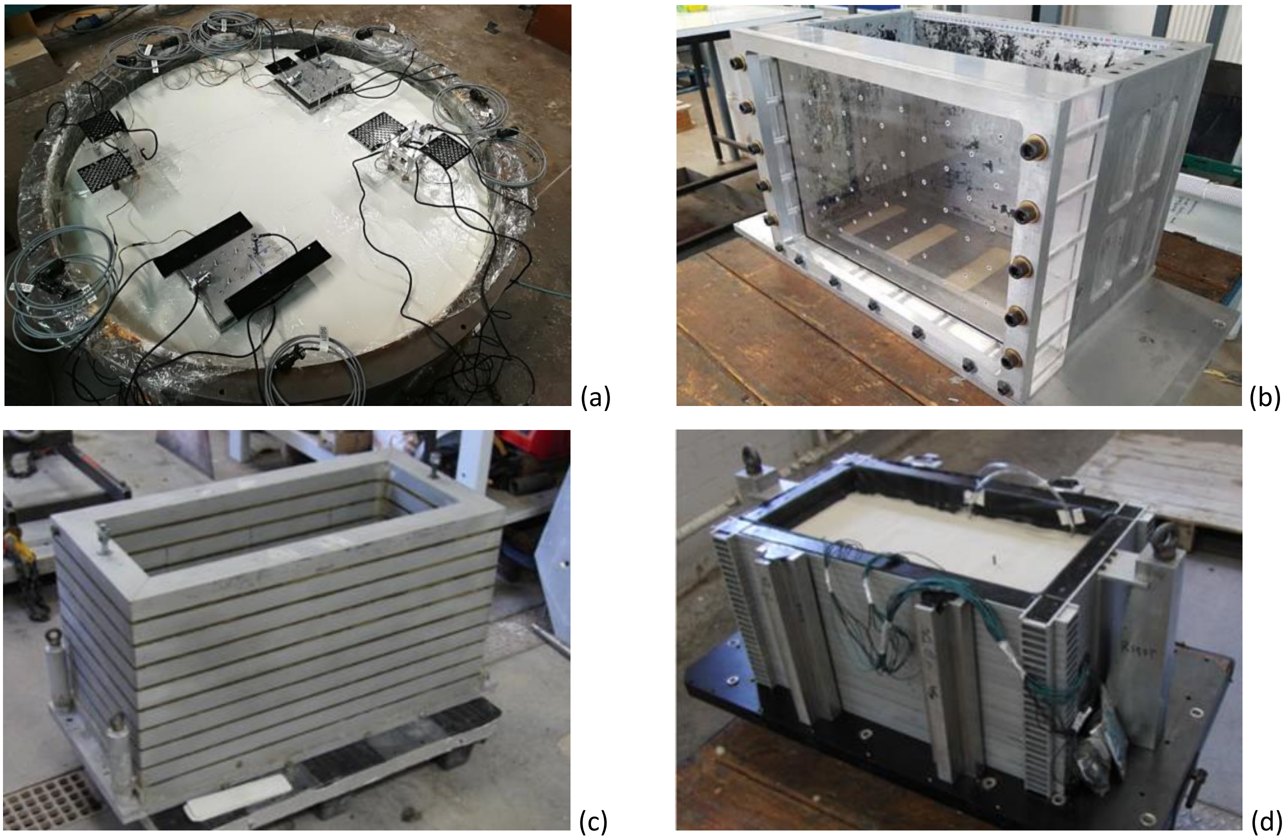


Figure 60 Model containers
(a) cylindrical tub, (b) windowed strongbox for PIV, (c) Equivalent Shear Beam (ESB), (d) laminar box

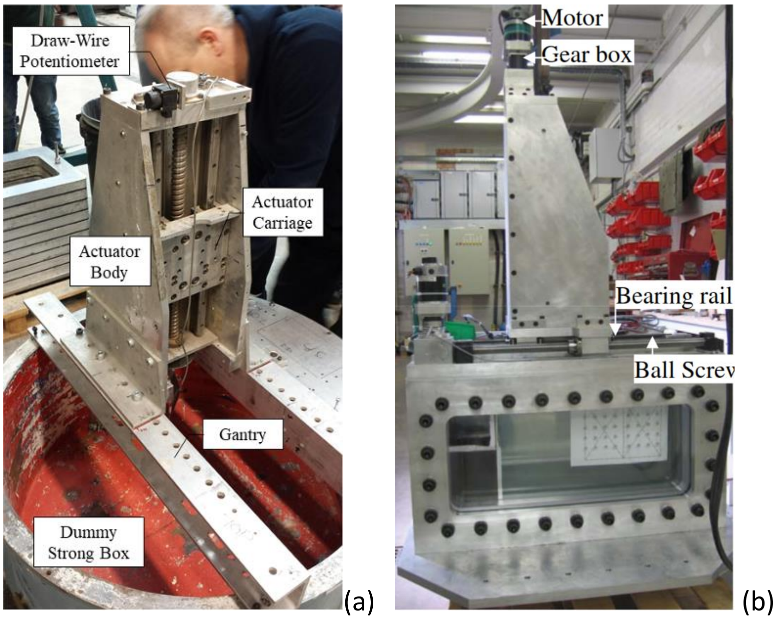


Figure 61 Quasi-static actuators:
(a) 1D actuator; (b) 2D actuator on a windowed centrifuge strongbox


(a)


(b)

Figure 62 (a) Stored Angular Momentum (SAM) actuator (b) Servo hydraulic earthquake actuator

Figure 63 Clay mixer

(a)

(b)

Figure 64 (a) hydraulic presses (b) pneumatic press

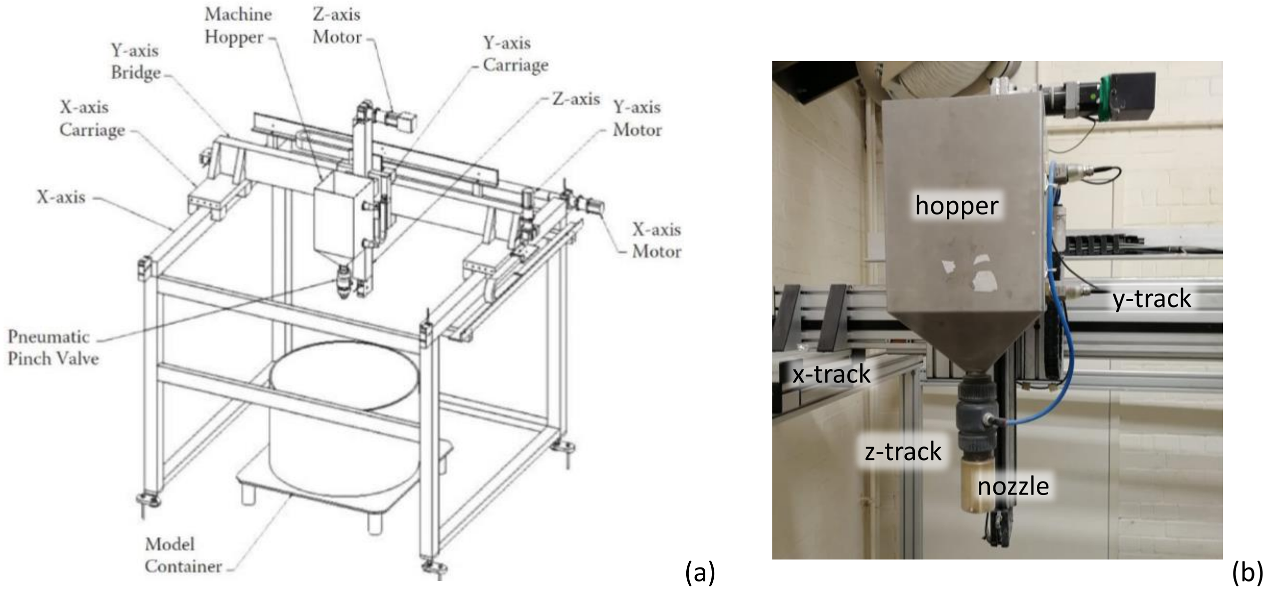


Figure 65 Sand pourer: (a) schematics, (b) detail of sand hopper and nozzle

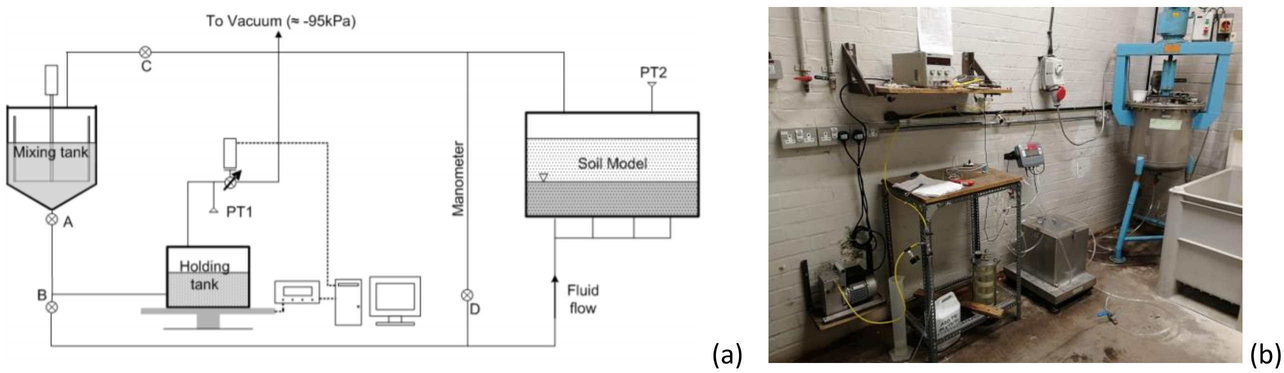


Figure 66 CAM-SAT back saturation apparatus: (a) schematics (b) view

9.4 Sensors and instrumentation used in the facility

A wide range of sensors are available for use at the Schofield Centre including:

- Load cells with capacities from 50 N to 500 kN.
- Various LVDT in ranges from 10 mm to 300 mm.
- String potentiometers for ranges > 300 mm.
- Piezo accelerometers with ranges from 1g to 100g.
- MEMS accelerometers with ranges from 1g to 100g.
- Tekscan pressure mapping system (link)
- Druck PDCR81 1 MPa pore pressure sensors
- Miniature cone and T-bar penetrometers; see Carey *et al*. (2018)
- Air hammer for shear wave sample profiling

Besides these generic sensors, the Schofield Centre has in-house manufacturing capabilities to develop custom instrumentation as required. For example, miniature piles can be strain gauged in order to measure bending moments during model tests.

9.5 Test description

9.5.1 Type of tests/Problems that can be explored

Over the forty years the Schofield Centre site has operated, a wide range of problems have been explored, including, but not limited to:

- Foundation response to uniaxial and combined loading
- Embankment and engineered slope performance
- Pile capacity (axial and lateral)
- Seismic resilience of foundations (liquefaction beneath shallow foundations and piles etc.)
- Pipeline or cable stability
- Tunneling processes including interaction with other tunnels, buildings and piles
- Construction processes (*e.g.* staged excavation of boxes and shafts in sand and clay)
- Influence of scour on foundation stability
- Building settlement interactions
- Penetrometer testing for in-situ profiling
- Image-based analysis of mechanisms using Particle Image Velocimetry (PIV)

9.5.2 Material suitable for the tests

The material types typically tested in the centrifuge at the Schofield Centre are:

- **Sand** - Hostun sand is the main type of sand used in current Schofield Centre research due to its economic cost and excellent liquefaction characteristics (for earthquake engineering research). Leighton Buzzard sand has been used at the Schofield Centre and remains available in small quantities in all popular fractions.
- **Clay** - The main type of clay used in the Schofield Centre is Speswhite Kaolin clay, which has been widely used in geotechnical physical modelling and has been widely characterized by many research groups.
- **Other** - Other types of soils (*e.g.*, site specific) can be tested in both geotechnical centrifuges available at the Schofield Centre, provided that sufficient material is made available to fill the desired strongbox. However, the impact of any sample reconstitution process needs to be well understood.

9.5.3 Test system limitations and constraints

It is not possible to spin the centrifuge overnight. This precludes the production of normally consolidated samples often desirable for offshore geotechnical engineering research. Other constraints mainly relate to the height of apparatus that can be placed on the swing arm of the beam centrifuge and within the channel of the mini drum centrifuge. For the former, the limits depend on the choice of centrifuge strongbox and in the latter on whether the inner tool table needs to move independently of the drum containing the soil sample. Balance calculations and structural calculations showing that the complete test set-up is able to withstand the gravitational force during test must be approved by an authorized member of the Schofield Centre. In no case will a test be performed without Schofield Centre staff.

9.6 Examples of relevant projects performed in the facility

The following sections provide examples of data and relevant projects performed in the facility, under the two main areas of underground construction and slopes.

9.6.1 Underground construction

Increasing urbanization means growing pressure for more housing and supporting infrastructure in cities and towns. By 2050 the world population will be around nine billion, with two-thirds of that population living in cities. Such changes in society mean that creating space for underground living and storage could become increasingly relevant to relieve pressure on already densely-developed cities. A series of project were carried out at the Schofield Centre to examine a variety of problems connected to underground construction in the urban environment including the response of building to tunnelling, the effects of tunnelling on piled foundations, the interaction between new and existing tunnels, and the construction of deep shafts by staged excavation, and the long-term heave of basement slabs.

Building response to tunnel excavation

Extensive previous research demonstrated the significant potential to study tunnel-soil-structure interaction by reduced scale modelling in a geotechnical centrifuge. This projected addressed potential limitations connected to oversimplified building models, which may result in uncertainties when interpreting building response to tunnelling-induced subsidence. A parametric study of the interaction between a tunnel and a building was carried out using layouts similar to that in Figure 67(a).

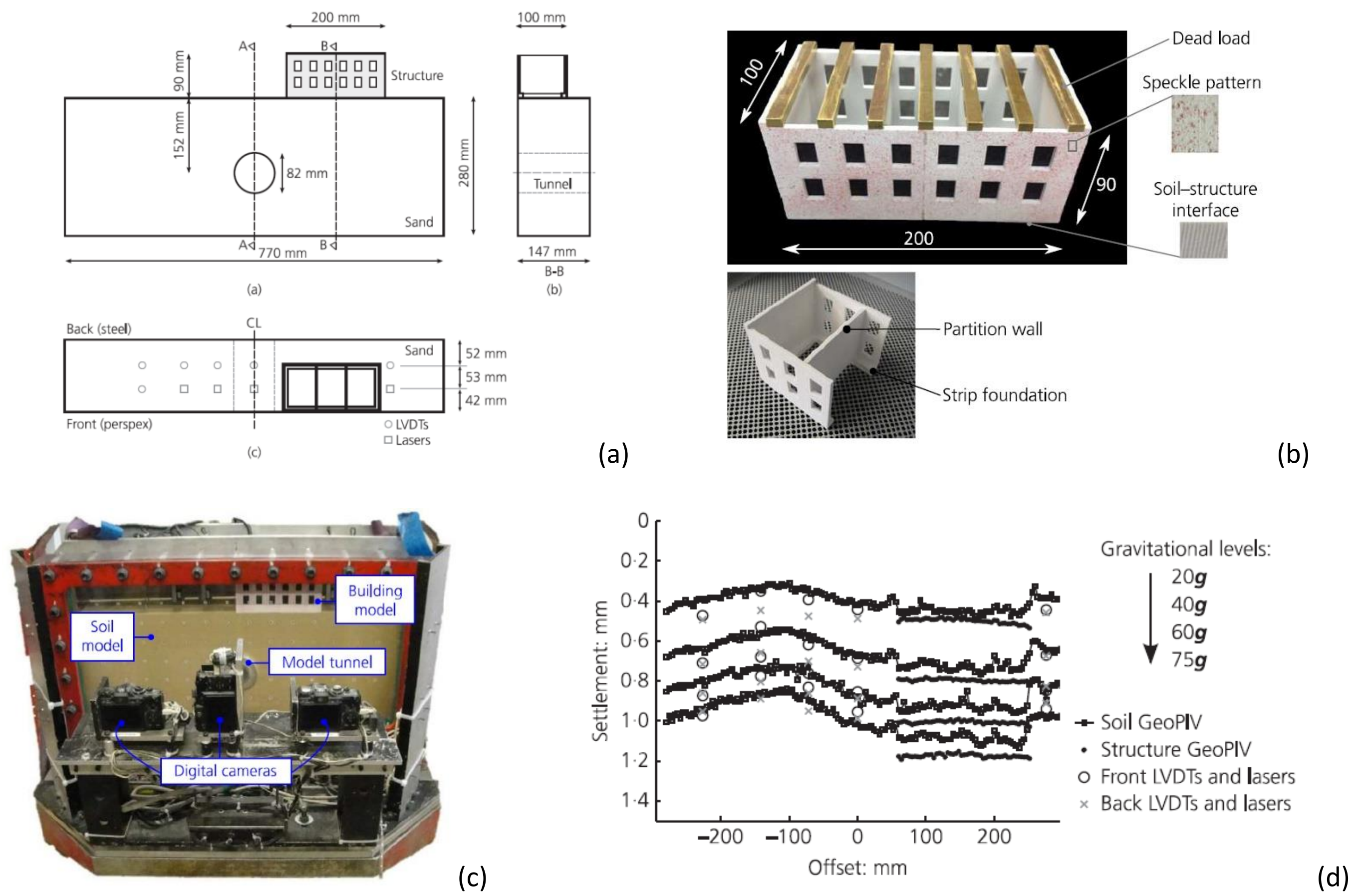


Figure 67 (a) Model layout, (b) three-dimensional printed building model, (c) image-base deformation measurement equipment (d) surface soil and structure movements during spin-up.

Powder-based three-dimensional (3D) printing was adopted to fabricate building models with realistic layouts, façade openings and foundations, see Figure 67(b). The 3D printed material had a Young's modulus and a brittle response similar to historic masonry. The building models included all main relevant features of the prototype such as building layout, strip foundations, rough soil-structure interfaces and window openings. To obtain realistic stresses beneath the foundation, dead load bars were placed on top of the buildings. The façade wall visible through the front window was speckled to enable DIC. Three digital cameras (Canon Powershot G10) were installed in front of the Perspex window to track ground and structure displacements using Digital Image correlation and Particle Image Velocimetry, Figure 67(c). In addition, laser displacement sensors and LVDTs monitored surface soil displacements. Figure 67(d), permitted to quantify boundary effects caused by friction between the Perspex and the soil.

Tunnelling Effects on Bored Piles in Clay

Centrifuge modelling was used to investigate the effects of tunnelling on bored piles in clay. A new centrifuge package, see Figure 68(a), including a system to model tunnel volume loss in 2D, an innovative reinforced composite pile, and a pile loading system, was designed. The model tunnel was an improved version of the model used by Marshall and Mair (2011). The pile loading system, see Figure 68(b) consisted of a piston, a load cell, a cable suspension, pile cap and pile guides. The model pile itself, see Figure 68(c) was manufactured as a composite of molded resin with aluminum reinforcement, which allowed strain gauging on a prepared and flat surface. Shear studs were added to ensure composite action between the resin and the aluminum section. To measure the axial load, full Wheatstone bridges with temperature and bending compensation were used at six positions along the model pile shaft.

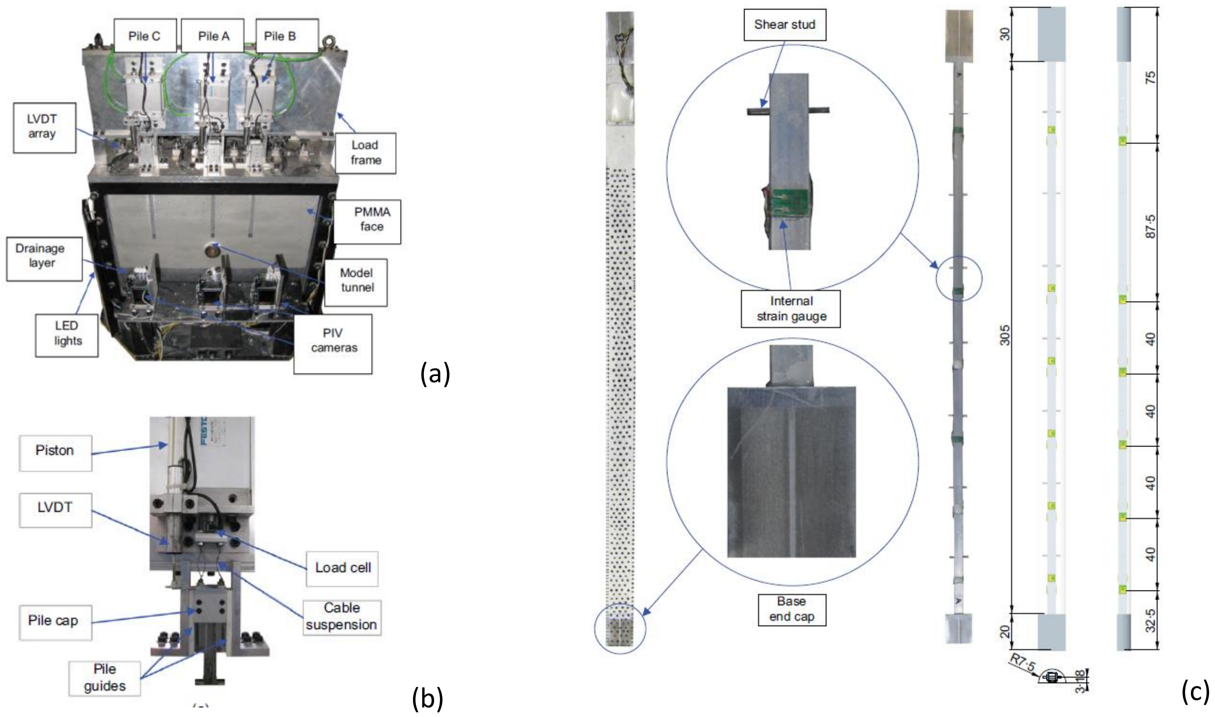


Figure 68 (a) pile-tunnel centrifuge package (b), pile loading system, (c) composite pile design and instrumentation

Particle Image Velocimetry (PIV) was used to monitor the soil and pile movements. The model piles were textured with dots to ensure high-quality PIV tracking of the pile displacements. Internal pile loads were inferred from strain gauges embedded in the piles, allowing measurement of the change in load due to soil-pile interaction. Combining this with the PIV measured movements, the load-transfer mechanism between the pile and soil was analyzed. The effect of pile factor of safety was seen to be significant in determining the pile head settlement when subjected to tunnelling movements. Pile positioning was also shown to be important, as were the effects of pile-soil stiffening and interaction effects between piles.

Tunnelling beneath an existing tunnel

This study built upon a field research project completed by the Centre for Smart Infrastructure and Construction (CSIC). In 2014, a team of CSIC researchers instrumented a 40-metre section of the disused, 100-year-old, 3 m-diameter cast iron Royal Mail Post Office railway tunnel during construction of Crossrail. Considerable uncertainty existed about the likely mode and levels of deformation to the existing tunnel network.

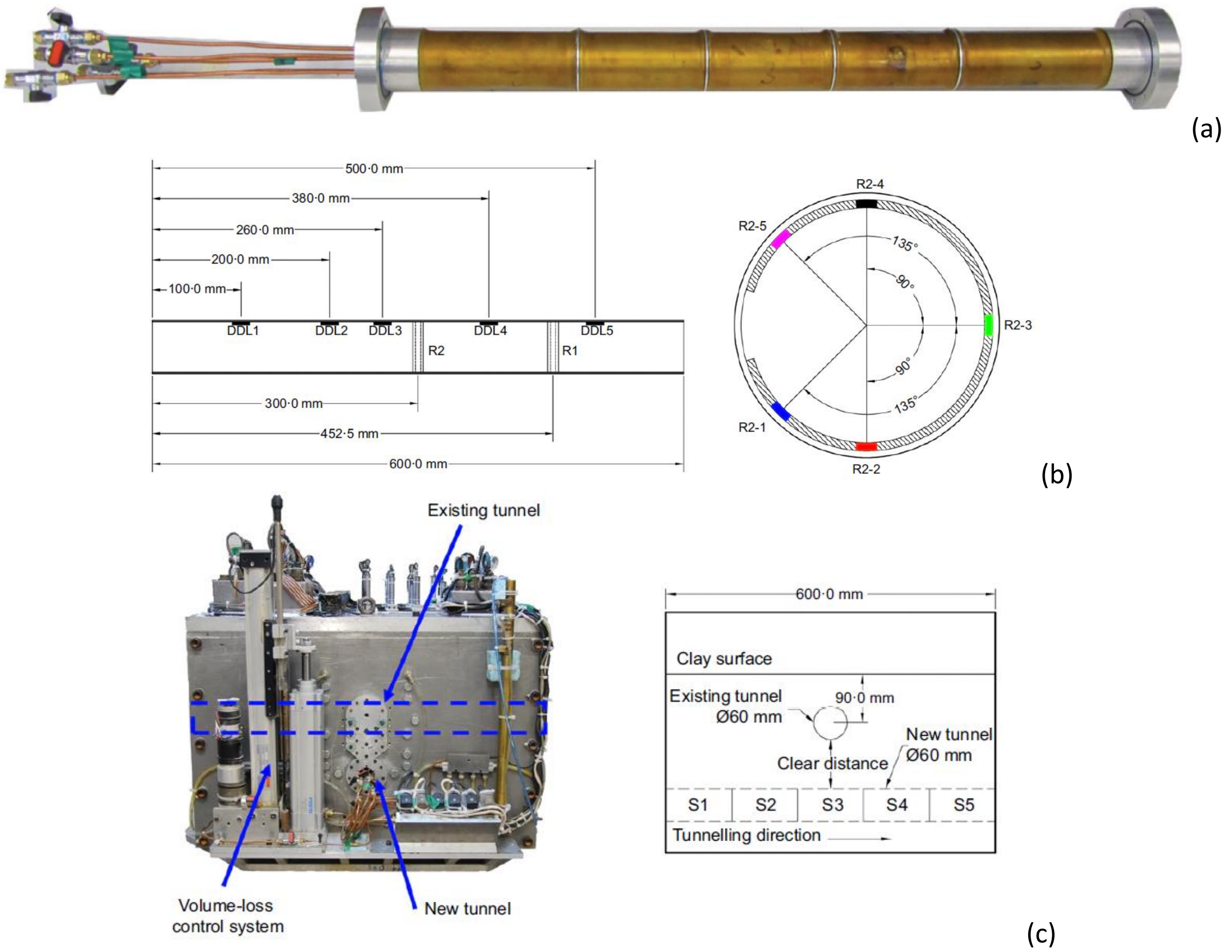
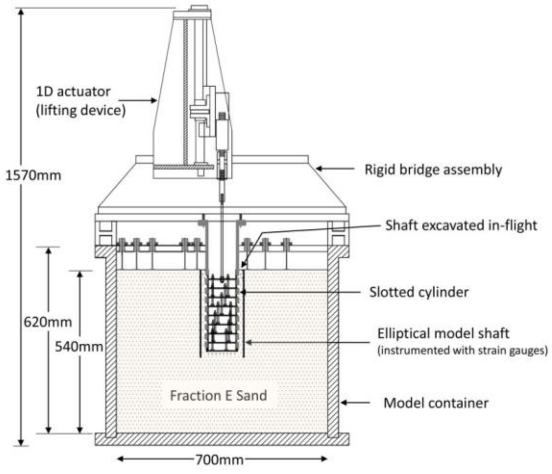


Figure 69 (a) Fully assembled staged tunnelling equipment, (b) layout of instrumentation in existing tunnel model, (c) front and side elevation of bespoke centrifuge package

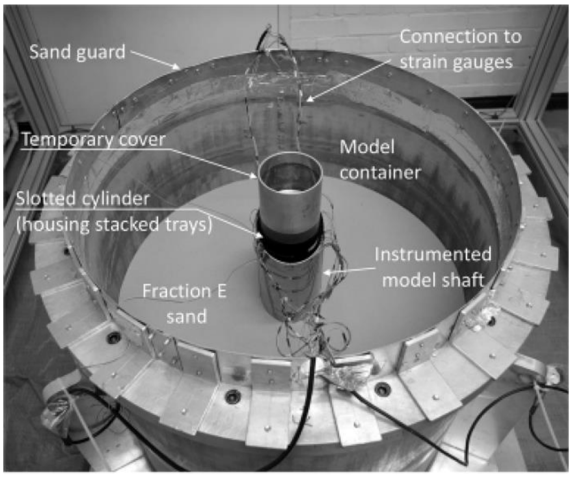
Tomake comparisons with the collected field data, a series of three-dimensional centrifuge tunnelling tests in clay were carried out in the Turner beam centrifuge at 100*g* to investigate the deformation mechanisms at realistic prototype scale stresses. Two tests were carried out with a clear distance between two tunnels at 0.5 and 1.5 diameter to investigate the difference in response. The diameter of the existing tunnel was kept constant at 60 mm along with a standard cover-to-diameter ratio C/D=1 for the new tunnel. As tunnelling is inherently a three-dimensional process, an approximate three-dimensional tunnelling system was designed to simulate the tunnelling sequence of a 62mm diameter tunnel in a series of five, 2D long advancements. The existing tunnel was modelled using a 60 mm OD aluminum tube with a 1.5 mm wall thickness and was instrumented with strain gauges to measure longitudinal and bending strains. A bespoke centrifuge package of internal dimensions W×L×D=750×600×440 mm^3 was designed and built to minimize soil disturbance during model preparation. To create realistic tunnelling conditions the clay (Speswhite kaolin) was pre-consolidated at 1g to a maximum effective vertical stress of 400kPa.

Staged excavation of shafts

At present, there are relatively few well-documented case studies of shaft construction, making it difficult for designers to estimate reliable ground movements. This study collected field observations of ground surface settlement during the construction of 27 circular shafts built for three major tunnelling projects in London: Crossrail, National Grid's London Power Tunnels project and Transport for London's Northern line extension and compared them to the results of a series of centrifuge tests in which staged excavation of circular and elliptical shafts in sand and circular shafts in clay was simulated in flight.

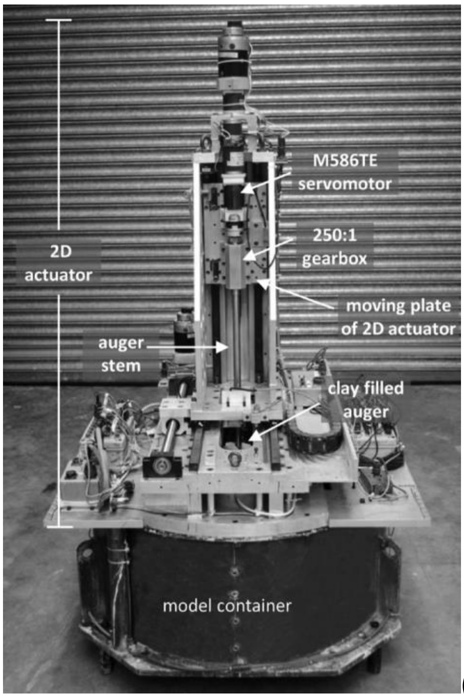


(a)

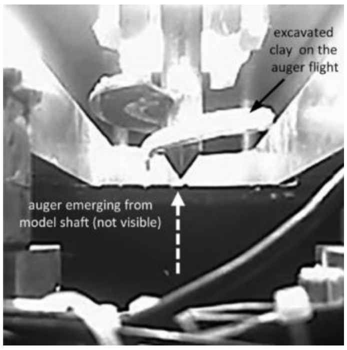


(b)

Figure 70 Staged excavation of shaft in sand (a) schematics, (b) view of model during preparation



(a)



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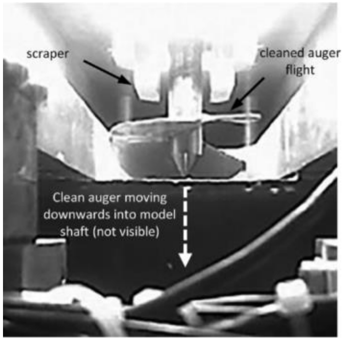

(c)

Figure 71 Staged excavation of shaft in clay (a) centrifuge package, (b) auger filled with clay as it emerges from shaft (c) auger travelling back to shaft after the clay has been cleared off the blade.

The system to excavate the shaft in sand, see Figure 71, consisted of (i) a bridge a rigid bridge spanning the model container to provide support to the main excavation system, (ii) a 104mm diameter slotted cylinder positioned at the center of the shaft, and supported from above, (iii) 9 steel trays stacked above each other inside the slotted cylinder, (iv) a vertical 1D actuator connected to the stacked trays via a stainless steel rod and a load cell. Staged excavation was activated by lifting each tray sequentially by 20 mm. At the start of the excavation, the stacked trays covered the openings in the slotted cylinder; when each tray was lifted, the opening was exposed thereby allowing sand in the annulus to flow through the opening and into the underlying tray. A miniature auger excavator was developed to excavate the model shaft in clay in-flight, see Figure 71. The system consisted of: (i) a single flight auger, (ii) a two-axis servo-actuator (2D actuator) and (iii) a mechanical device to remove the excavated clay from the auger after each excavation step. The single flight 88mm outer diameter auger was used to core clay from the center of the shaft. A servomotor allowed the auger to rotate, while the 2D actuator enabled movement of the auger in the horizontal and vertical direction. A 35mm square, aluminum block (scraper) that could travel vertically via an electromechanical linear actuator was used to remove the clay from the auger after each excavation step. In both cases longitudinal bending and hoop strains in the shaft were measured during excavation using four arrays of strain gauges, and ground surface settlement at varying distances from the shaft were measured using LVDTs.

9.6.2 Slopes

Research is carried out at the Schofield Centre to address the resilience of UK infrastructure affected by the physical impact of climate variability and change. Failure of highway and railway UK engineered slopes (embankments and cuts) is relatively frequent and requires continuous maintenance and repair by infrastructure owners. An increased understanding of the mechanisms affecting earthworks failures will significantly improve the ability to design, construct and maintain resilient and safe infrastructure, with the potential to improve the reliability of service provision, increase asset life and protect asset returns.

Seasonal ratcheting and softening in clay slopes

Centrifuge tests have been carried out on kaolin clay slopes subject to variations in surface rainfall and humidity corresponding, at model scale, to successive wet and dry seasons in the field. Using the accelerated time-scaling provided by centrifuge modelling it was possible to observe the behavior of over-consolidated clay embankments during many "years" of seasonal pore pressure cycles.

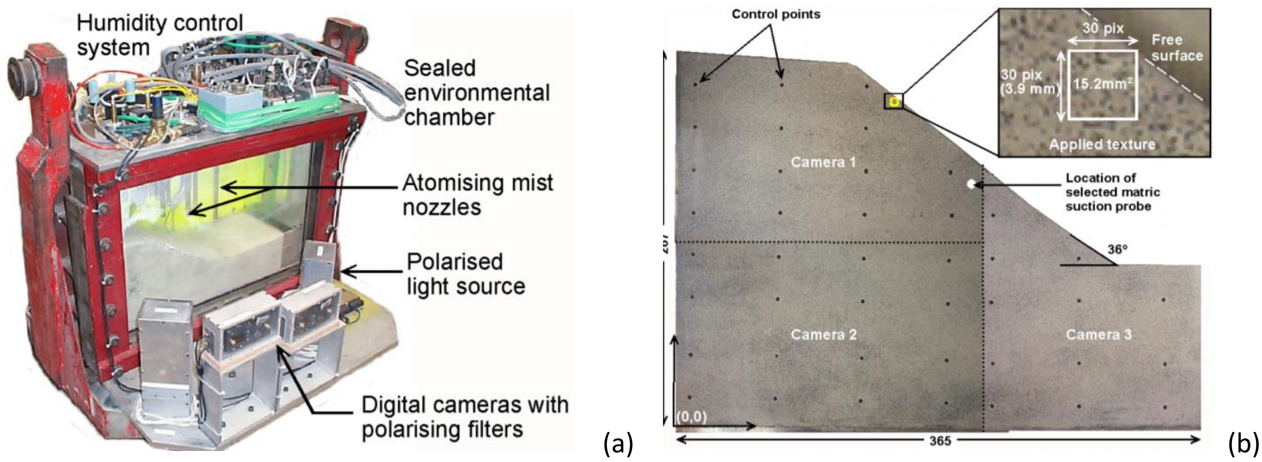

Figure 72 (a) Atmospheric chamber and digital acquisition system (b) location of deformation and pore pressure measurements on model over-consolidated clay slope

Seasons were created using an atmospheric chamber in which the relative humidity boundary condition above the surface of the model embankment is controlled, see Figure 72(a). This boundary condition is translated by the soil into seasonal pore water pressure variations - predominately negative during the dry season and positive (or nearly positive) during the rainfall infiltration of the wet season. The model slopes were instrumented with miniature high-capacity tensiometers, and the deformations of their cross-sections were observed by digital photography and analyzed by particle image velocimetry, see Figure 72(b). Sequences of swelling and shrinkage have been seen to be potentially irreversible, leading to creep in the form of down-slope ratcheting, accompanied by progressive regional softening within the zone affected by the seasonal moisture movements. Ultimately, this regional softening has been seen to lead to slope failures, in which segments of soil have separated from the mass through the opening of tension cracks and the formation of a localized shear rupture.

Low-cost digital image correlation and strain measurement for slope modelling

Particle image velocimetry (PIV), or digital image correlation (DIC), is a widely used technique to measure soil displacements and strains in small-scale geotechnical models through a transparent window, see Figure 73(a). A study was performed to examine the slope failure of an embankment that was loaded at the crest of the hill by a shallow strip footing. The slope failure was initiated by loading the footing until the soil sheared.

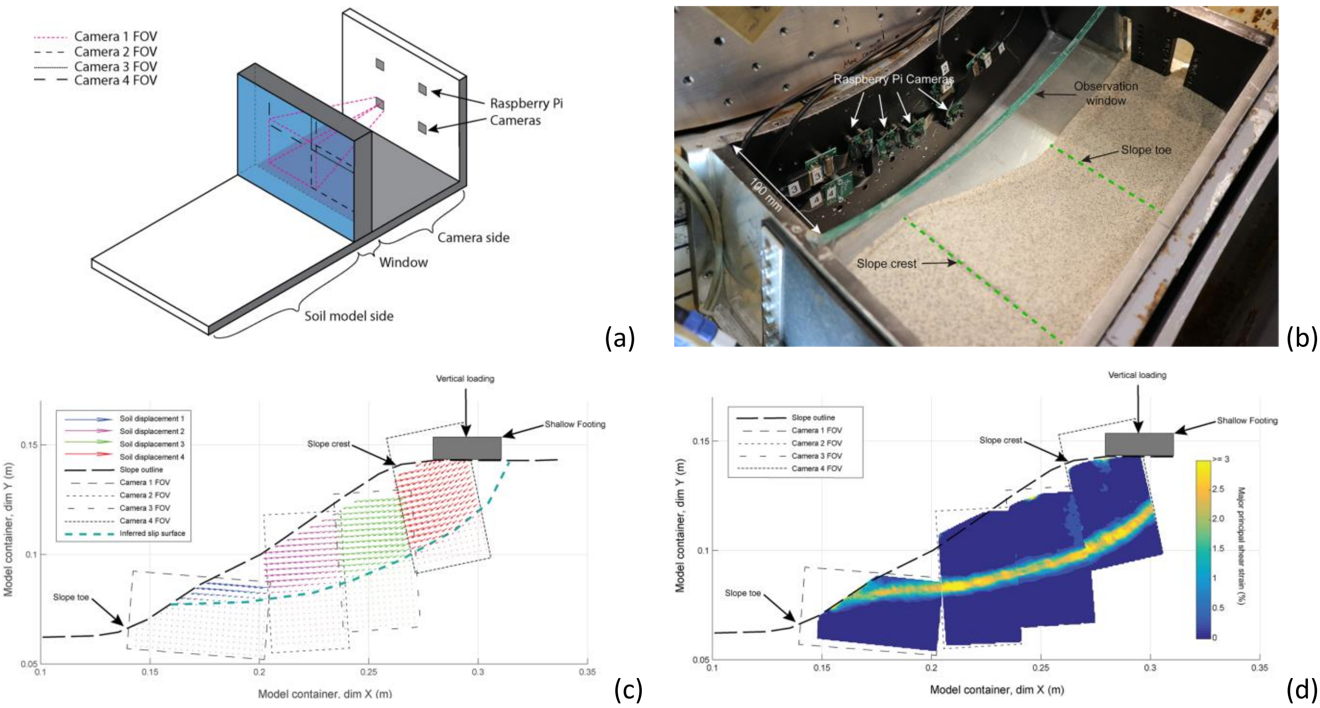

Figure 73(a) Typical PIV/DIC test set-up for geotechnical centrifuge modelling, (b) view of centrifuge model set-up showing slope and camera configuration, (c) displacement field, (d) major principal strain

The soil displacement mechanisms were recorded in the minidrum centrifuge using 1080p HD video captured on four Raspberry Pi 3B+ SBCs and Model 2.1 cameras, through a toughened glass window separating the soil side from the camera side of the experiment, see Figure 73(b). One of the challenges in this case is the limited space - the cameras have a distance from the side wall of the container to the glass of only 100 mm. The soil displacement measurements from each of the four cameras are plotted in the same real-world reference frame in Figure 73(c), whereas the incremental strains calculated for each camera, and the major principal strain field is shown for the slope in Figure 73(d) showing that it is possible to identify the shear band localization at the slip surface within the slope.

Inspired by the use of unmanned aerial vehicles by surveyors, reproducing 3D-point clouds of real landslides as a cost-effective alternative to more traditional, and expensive LiDAR surface scanning, close-range multi-camera photogrammetry was also developed to carry out surface topography measurements to capture the full field soil displacements in centrifuge modelling of the interaction between a landslide and a buried utility. The stereo photogrammetry method consists of digital image acquisition, followed by identification of tie-points using a scale invariant feature transform (SIFT) in order to identify pixel groups shared by multiple images. One of the benefits of using this method is the possibility to place the cameras without needing to know their position relative to each other or to reference markers.

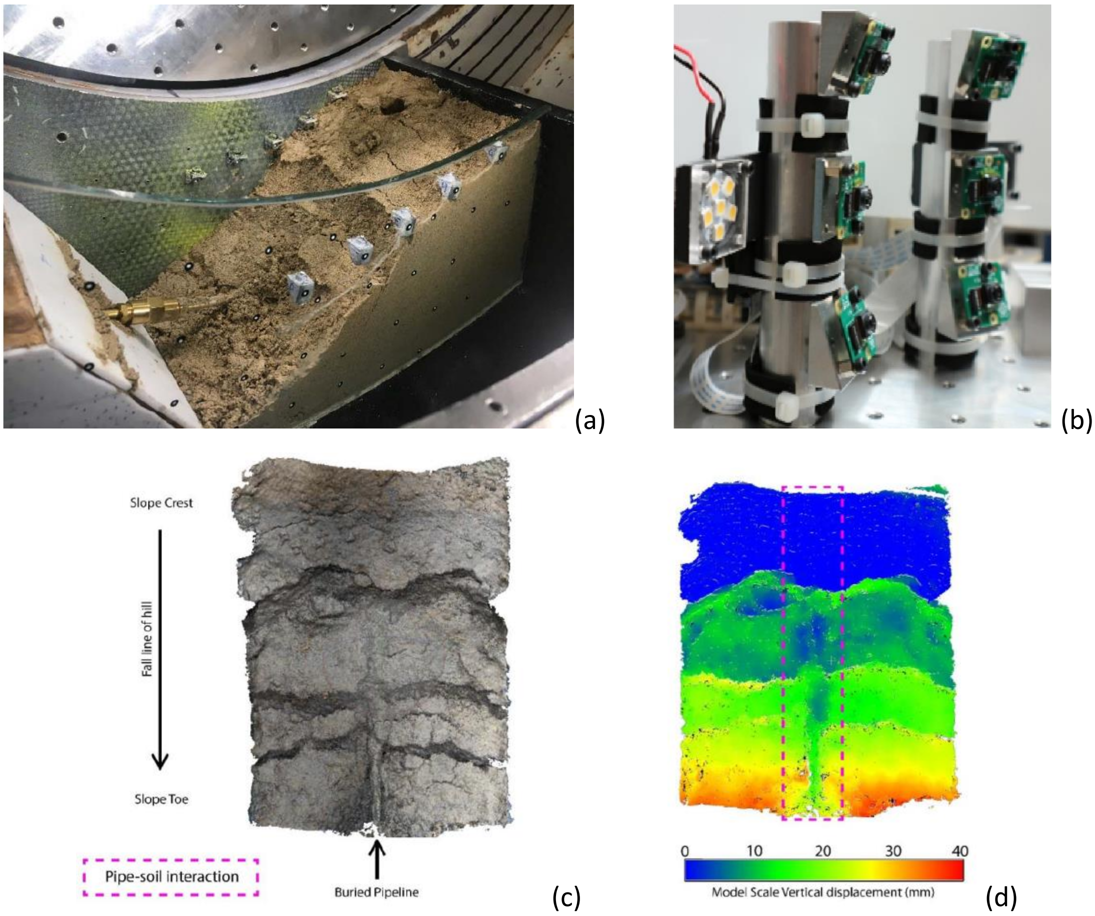

Figure 74 (a) Photograph of Centrifuge model slope post-landslide (b) Raspberry Pi Multi-Camera (c) 3D point cloud of landslide surface, (d) vertical displacement raster map

The drum centrifuge was instrumented with eight Raspberry Pi single board computers (SBC) and eight Raspberry Pi Cameras (version 2.1), which are 8-megapixel adjustable focus, single board cameras. Figure 74(c) was constructed photographing the surface at an approximate distance of 200 mm (model scale). The resulting vertical displacement map between t = 0 and t = 65 s, at the end of slope failure can be seen in Figure 74(d).

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9.8 Other relevant information

Besides the Schofield Centre, the Geotechnical and Environmental Engineering Research Group at Cambridge has extensive facilities for laboratory testing, sensor development, and numerical analysis. The Schofield Centre operates in close collaboration with the recently established National Research Facility for Infrastructure Sensing (NRFIS) hosting a number of laboratories including: Sensor Development (Novel Prototyping, Maintenance, Vibration Isolation, Smart Infrastructure and Construction), Structures (Materials, Concrete Innovation, Strong Floor), and Geomechanics (High Pressure, Unsaturated, Thermo-Hydro-Mechanical).

10 TUDa Geotechnical Test Pit (Technical University of Darmstadt)

10.1 Basic information

Table 25 shows basic information of the facility.

Table 25 Basic information of TDUa Geotechnical Test Pit

TUDa Geotechnical Test Pit	
Name (short)	TUDa Geotechnical Test Pit
Name (long)	GTP
Owner	Institute of Geotechnics, Technical University of Darmstadt
Location (City/Country)	Darmstadt, Germany
Address	Günter-Behnisch-Straße Gebäude L05/04 64287 Darmstadt
Website (vernacular language)	https://www.geotechnik.tu-darmstadt.de/forschung_ivg/forschungseinrichtungen_ivg/versuchshalle_ivg/index.de.jsp
Website (English)	https://www.geotechnik.tu-darmstadt.de/forschung_ivg/forschungseinrichtungen_ivg/versuchshalle_ivg/index.en.jsp
Contact (e-mail)	Mary Antonette Beroya-Eitner (ma.beroya-eitner@geotechnik.tu-darmstadt.de) Marc Schneider (m.schneider@geotechnik.tu-darmstadt.de)
Head of facility (name/e-mail)	Hauke Zachert / zachert@geotechnik.tu-darmstadt.de
Construction year	1970

10.2 Scope of the facility

The TUDa Geotechnical Test Pit (GTP) is a testing facility mainly for studying soil-pile interaction, although in principle, investigation of other geotechnical problems is also possible (cf. Sections 10.5.3 and 10.6). The facility allows for near- to full-scale testing (e.g., micropiles), as well as medium- to large-scale model testing, thusbeing able to close the gap between small-scale testing, on one hand, and very rare and expensive in-situ testing, on the other. The facility also overcomes some of the limitations of centrifuge testing such as scalability of the soil/soil grain. As such, phenomena that are usually difficult to observe, as for instance soil-water interaction, can be better investigated. With its capability, the GTP can provide valuable contribution in the testing and validation of existing physical theories and numerical models, as well as in the development of new ones.

10.3 Facility physical description / Technical specifications

Located in a 23 m x 23 m x 7 m (L x W x H) experimental hall of the Institute of Geotechnics, GTP has a total length and width of 19.5 m and 5 m, respectively. It consists of a stiff concrete box caisson, the lateral and bottom boundaries of which are rigid. It has two parts: a 6 m deep pit with plan dimension of 5 m x 4.35 m and a shallower pit 3 m in depth and plan dimension of 14.5 m x 5 m. In the latter pit, mobile walls can create smaller sections to allow for smaller-scale tests. In addition, a 4.3 m x 3 m (diameter x height) steel cylinder is available that has water connections at the bottom and thus where saturated testing can be performed.

The facility is equipped with vertical and horizontal actuators that can transmit static and dynamic force or displacement to the pile/foundation. Both the vertical and horizontal loading frames are movable and can be positioned at various places across the pit to accommodate different test and loading conditions. Table 26 gives further details on the technical specifications of the GTP, while Figure 75 shows an overview of the facility.

Table 26 TUDa GTP Technical Specifications

Parameter	Value
Test Pit Dimension	19.5m x 5.0m (L x W)
Deep Pit	5.0m x 4.35m x 6.0 m (L x W x H)
Shallow Pit	14.5m x 5.0m x 3m (L x W x H)
Steel Cylinder	4.3m x 3m (D x H)
Test Type	
Pit	Dry Testing
Steel Cylinder	Wet Testing
Test Material	Medium Sand
Model Preparation	Dry Pluviation; Moist Tamping-Layer Wise Compaction
Pile Type	Steel, Concrete, Timber
Typical Single Pile Size	
Diameter	100 ≤ D ≤ 500 mm
Length	1000 ≤ L ≤ 4000 mm
Pile Groups	Feasible
Pile Installation	Drop Hammer; Vibrohammer; Wish-in-Place
Instrumentation	Load Cells, Displacement Transducers, Pore Water Transducers, Strain Gauges *(see also Section 10.4)*
Vertical Load	
Static	Up to 2000 kN
Cyclic	Up to 100 kN @ 2 Hz
Horizontal Load	
Static	Up to 1000 kN
Cyclic	Up to 100 kN @ 2 Hz

a)

b)

c)

Figure 75 Overview of the TUDa Geotechnical Test Pit:
(a) The deep pit (5 m x 4.35 m x 6 m) in the foreground and shallow pit (14.5 m x 5 m x 3 m depth) in the background. For the latter, mobile walls can create smaller sections to allow for smaller-scale tests; (b) Axial loading of steel pile; (c) The hydraulic cylinders in the foreground, which can be attached to both horizontal and vertical frames. In the background is the steel cylinder about 3m deep and 4.3 m in diameter. Equip with water connection, wet testing is done in this cylinder

10.4 Sensors and instrumentation used in the facility

Sensors and instrumentation available for used in the facility are detailed in Table 27 below.

Table 27 Sensor and instrumentation of TDUa GTP

Measured physical parameter	Type of sensor	Description	Measurement range	Accuracy
Displacement	Linear variable differential transformer	HBM W10/10K/10TK HBM W20/20K/10TK HBM W50 HBM W100/100K HBM W200	20 mm 40 mm 100 mm 200 mm 400 mm	± 0.2 % ± 0.2 %
	Potentiometric displacement transducer	NovoTechnik TRS/25	30 mm	± 1.5 mm
	Incremental linear transducer	Megaton MS50TS TTL 10	50 mm	± 5 %
	Dial gauge/ Precision measurement clock	Sylvac 50mm/0.001	50 mm	0.001 mm
Strain	Strain gauges	Several types for different materials and different testing conditions	variable	variable
Distance	Z+F Imager 5016	Terrestrial 3D Laser Scanner for generating digital and differential models	Up to 360 m	1-2 mm depending on surface conditions
Load	Load cell	HBM S2 HBM S9/2KN-50KN HBM S9M/10KN-20KN HBM C1 HBM C2/5KN-20KN HBM C3H3 HBM U1 HBM U2B	500 N 2 KN - 50 KN 10 KN -20 KN 50 KN 5 KN - 20 KN 5 KN 5 KN	± 0.05% ± 0.05% ± 0.02% ±0.1% ±0.1% ±0.1%
Pressure	Absolute pressure transducer	HBM P3M/10-100 bars HBM P3MA/500-1000 bar HBM P3MB HBM P6 HBM P8AP	10-00 bars 500-1000 bars 10 bars 20 bars 500 bars	± 0.25% ±0.2% ±0.2% ± 0.1%
	Relative pressure sensor	HBM P11/0.2-2 bars MessOtron MP621	10 bars	
	Differential pressure sensor	HBM PD1/0,1	50 bars	
	Pore pressure gauge	TML/ Glötzl different models	Model-dependent	
	Soil pressure gauge	TML/ Glötzl different models	Model-dependent	

Measured physical parameter	Type of sensor	Description	Measurement range	Accuracy
Temperature	Thermographic camera	FLIR T335 (30 Hz)	-20°C to 650°C	± 2°C
	Resistance thermometer	Pt100/varying sizes		±0.1 K up to ±0003K at 0°C (1/10 DIN up to 1/3 DIN)
Matric suction	Mobile tensiometer	UGT Tensio 100	0-85 kPa	±0.01 bar
	Miniature tensiometer	UMS T5-15	-1000 hPa to 850 hPa	± 0.5% FS
Moisture content	Soil moisture sensor	TRIME TDR	0 % to 100%	± 2%
Acceleration Forces	Accelerometer	B12/200 B12/500	±200 m/s² ±1000 m/s²	±2% ±2%
Measurement and control system	Data logger	Campbell Scientific CR1000		
	Multiplexer	AM16/32B Channel Relay Analogue Multiplexer		
	Vibrating wire spectrum analyser module	AVW200 2-Channel		
	Ethernet and compact flash module	NL115		
	HBM 8-channel simultaneous measurement	Quantum X with associated software CATMAN AP		
	HBM 8-Channel simultaneous measurement	Spider 8 with associated software CATMAN AP		

In addition, a cone penetration test unit with pore water pressure measurement (CPTu) is available. The unit has digital piezocone with a cross sectional area of 10 cm². Maximum capacity is 100 MPa for cone resistance (q_c), 1 MPa for shaft friction (f_s) and 2 MPa for pore water pressure (u). Inclination XY is±15°.

A particle image velocimetry (PIV) system is also available (Camera model: Phantom Micro M/LC; evaluation software: Insight 4G), but its use would require certain modification of the facility.

10.5 Test description

10.5.1 Test Material

The facility uses Darmstadt Sand as the standard test material. Sourced from the Main River, the material is a poorly graded clean silica sand. Individual particles are cubic in form, with sharp to well-rounded edges and rough surface (Figure 76). Table 28 gives the physical properties of the sand. Tests for these properties are in accordance with the German DIN (Deutsche Institut für Normung e.V.) Standards.

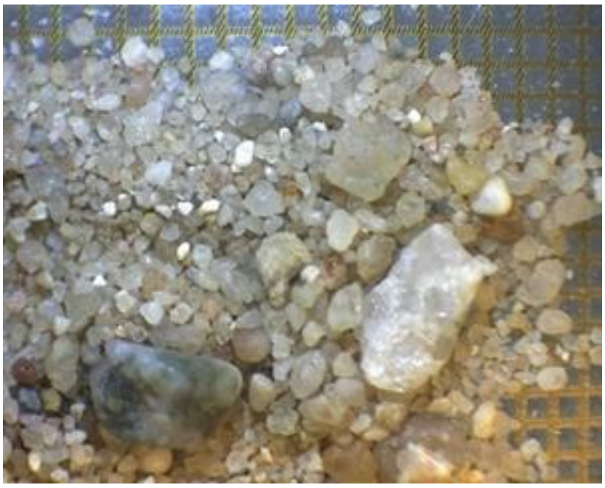

Figure 76 Darmstadt sand particle characteristics

Table 28 Physical properties of Darmstadt Sand

Parameter	Value
Shape, angularity and texture	Cubic, sharp edged to well rounded, rough surface
Mean particle size, D_{50} (mm)	0.48
Coefficient of Uniformity, *Cu*	2.41
Coefficient of Curvature, *Cc*	0.98
Specific Gravity, G_s (g/cm³)	2.617
Minimum void ratio, e_{min}	0.459
Maximum void ratio, e_{max}	0.803
Minimum dry density, γ_{min} (g/cm³)	1.462
Maximum dry density, γ_{max} (g/cm³)	1.807

10.5.2 Model Building

In the GTP, two methods are adopted for soil model building, corresponding to the two types of testing that can be performed in the facility: Air Pluviation Method for Dry Testing and Moist Tamping-Layerwise Compaction for Wet Testing.

Air Pluviation Method: This method is widely used for preparing large sand layers of desired densities for laboratory studies as it allows building a uniform and highly repeatable soil model. In the GTP, the pluviation system consists of a sand hopper with a volume capacity of ca. 1 cu.m and 4 rigid tubes (Figure 77). The system is attached to the crane, which is electronically controlled to traverse the pit back and forth. Sand flow is controlled through the slots at the nozzles of the hopper, which together with the height of fall determine the density of the soil model.

Moist tamping-Layerwise Compaction: This method is practical for handling moist sand and therefore most suitable for wet testing, which as mentioned above is performed in the steel cylinder. In the Moist Tamping Method, the number of layers is predetermined. Knowing the volume of each layer, the mass of soil required to attain the target density can be calculated. The soil is then poured into the cylinder and tamped uniformly at set layer height. A rotating laser is used to ensure that the surface of the soil layer is even and levelled to the same height.

Figure 77 The Dry Pluviation System consisting of a sand hopper and four rigid tubes

10.5.3 Types of tests/problems that can be explored

Among the general topics that can be explored in GTP are as follows:

- Soil-pile behaviour under static/dynamic axial and/or horizontal loading
- Pile group effects
- Pile installation effects

As noted earlier, however, other studies not involving piles are also possible. Examples include testing of new installation techniques, prototype foundation or ground improvement methods. In addition, the behaviour of other geo-structures such as shallow foundations, (reinforced) embankments and buried structures like pipes or cables can also be investigated.

10.5.4 Test system limitations and constraints

Due to the limitations imposed by the pit dimension, the ideal single pile size range that can be tested in the pit is 100 - 500 mm in diameter and 1000 – 4000 mm in length. Ideal pile type is steel. Where other pile types are desired, ample time must be given so that adjustments can be made in the system. In some cases, Users may need to provide required accessories, as for instance the pile cap for drop hammer-driven concrete piles. Testing in the pit is limited to dry sand, although a steel cylinder is available for saturated testing. Currently, cyclic loading is limited to 2 Hz at small deflection range, but improvement to this capacity is underway.

10.6 Relevant projects performed in the facility and example of results

Settlement of Shallow Foundations

Supported by the German Federal Ministry for Research and Technology and the German Research Foundation (DFG), the aim of the study was to validate of the applicability of the elastic half-space model in the settlement calculation of small, isolated footing, as well as to develop, based on load plate test, the simplest possible procedure for calculating the settlement of the said type of foundation. In this regard, circular, rigid footing on sand was tested in a 5 m x 5 m area of the shallow pit. The tests were conducted at varying footing diameter and embedment depth. For the soil model, dry sand was used with a uniformity coefficient of 2.2. This sand was installed dense in the pit using air pluviation method since the trial tests showed that a homogeneous fill is best achieved at high density.

After sand and footing installation, the foundation was axially loaded in steps up to 2 MN. The settlement, as well as the horizontal and vertical displacements in the soil at each load increment were measured at a total of 81 points. The measuring points for the vertical displacement were arranged symmetrically about the central axis so that the extent by which the test soil had been evenly installed could be checked (Figure 78).

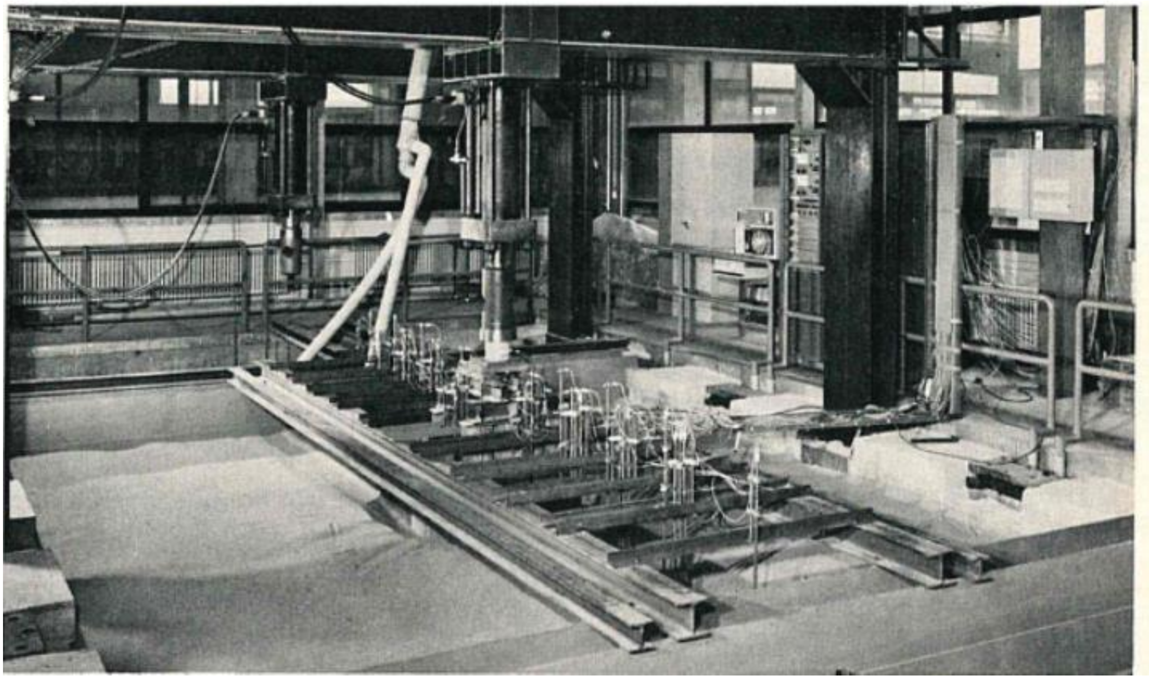

Figure 78 Experimental set-up showing the arrangement of the measuring devices

Results of the study showed how the soil underneath the isolated footing was displaced to the side of the footing. Settlement under the foundation was much more concentrated than is predicted under the theory of elastic half-space. With the theory, the extent of the spread of settlement on the sides of the foundation is particularly overestimated. Despite a continuous settlement depression, a punching-type failure was observed where a distinct change in the degree of settlement in the area close to the foundation was noticeable. Results of Finite Element Analysis showed that while the nonlinear elastic material model is generally applicable to large-area foundations, treatment of a small, isolated footing on sand requires an extended material model that takes into account the dilatancy of the sand.

Soil Mechanical Basis for Dimensioning Flexible Pipes for Sewers

In this project that was commissioned by the German Federal Ministry for Research and Technology, the deformation and load-bearing behavior of pipes were investigated in 8 model tests and a large-scale test. In the latter test, which was conducted in GPT, a plastic pipe 5 m in length and 1 m in diameter was laid over an approximately 1 m layer of sand, and then covered with another 4 m-thick layers of sand. The sand was installed using air pluviation method, through which a bulk density of 17.364 kN / m³ was achieved. The homogeneity of the soil layers was checked through SPT that was carried out after the test.

After sand installation, a strip load with a width of 1.0 m was applied on the surface in stages up to the maximum force of 1.7 MN (340 kN / m² for 1m x 5m strip). During sand pouring and load application, both the vertical and horizontal deformations were measured at 24 soil depths using inductive scanning sensor. Pipe deformation on the other hand was measured by wave scanning of the pipe wall.

The testing shows that the structural system consisting of the pipe and the soil should not be considered as a composite system in which the load bearing of the pipe can be increased through a higher soil-bedding reaction. Instead, the soil should be considered as the load bearing component with the pipe only providing the lateral support to maintain static equilibrium. The pipe then has to withstand only the stresses resulting for this equilibrium.

Results of the study served as input to the "Guideline for the Static Calculation of Drainage Canals and Pipes" that was being prepared by the Sewer Techniques Group (Abwassertechnische Vereinigung, ATV) at that time.

Study of the load-bearing behaviour of pile in radially prestressed soil

This project involved the experimental and numerical investigation of an axially-loaded single pile installed in sand to investigate the following:

- Quantitative relationship between the radial prestressing of the soil, peak pressure and skin friction
- Soil movement around the circumference of the pile during loading
- Influence of dilatancy on pile bearing behaviour and effect of radial prestressing of the soil
- Skin friction behaviour under periodically alternating loading and unloading

To this end, a research pile was developed that was equipped with measuring technology and which could be radially expanded in the soil. The pile has a length of 4 m and a diameter of 180 mm, which on expansion could increase to a maximum of 220 mm. This expansion mechanism is present in the lower two meters of the pile and involves inflating a rubber sleeve that is in the inner shaft of the pile. Thus, the application of radial stresses into the soil also only takes place in this area. The experiment is mainly intended to depict the load-bearing behavior of grouted piles.

The test was carried out in the 6 m-deep pit. For the soil model, dry sand was used. The pile was wished-in-place, with the sand poured around it using the sand rain method. An average soil sand dry density of 1.69 t / m³ was achieved. After pile installation, the radial pressure on the lateral surface was first set (between 0.0 and 450 kN/m^2), then the axial load was applied. Axial loading was done in steps of 50-60 kN / m² up to loads of 300-400 kN / m² and involved several loading and unloading cycles. Horizontal and vertical deformations were measured using 75 inductive displacement transducers. Moreover, 14 earth pressure transducers working according to the Glötzl principle were installed at the bottom part of the pit. The arrangement of the vertical and horizontal deformation measuring level as well as the earth pressure transducer are shown in Figure 79 below.

With the results of the tests, the basic mechanisms of pile load transfer could be described. The study also gave insights on the relationship between the radial stresses on the soil and the load bearing behaviour of the pile, as well as on the practical application of jacket grouting in increasing pile load bearing capacity. Recalculation of selected loading cycles using the Finite Element Method showed the possibilities and limits of the said method at that time. Of the three material models used – elastic, non-linear elastic and elastoplastic – the elastoplastic model proved superior, particularly in the simulation of pile load transfer without radial pre-stressing of the soil.

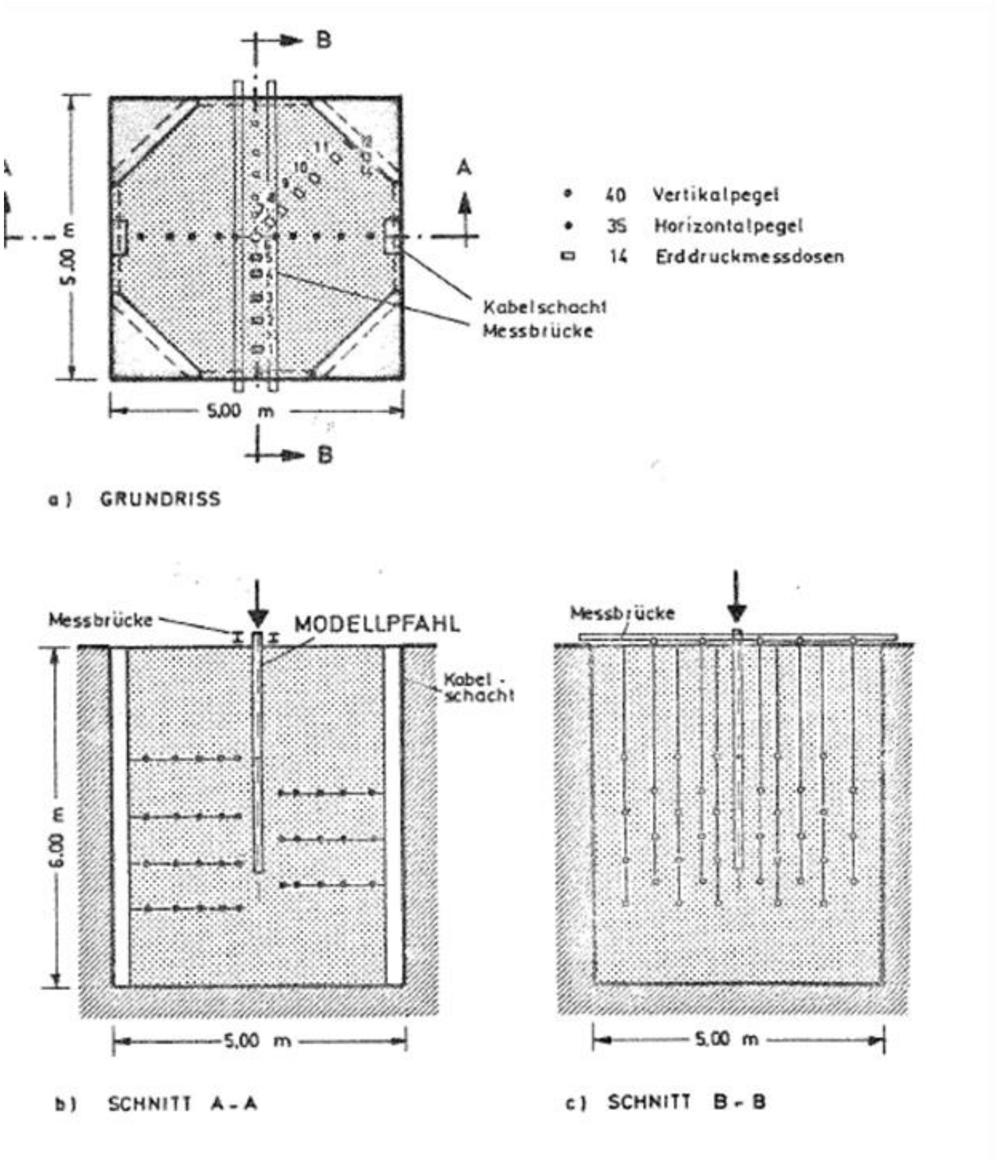

Figure 79 Test and instrumentation set-up

10.7 Reference papers

1- Breth, H., Arslan, M.U., Rückel, H. and Stroh, D. (1976). Zur Setzung von Flachgründungen. Vorträge d. Grundbautagung Nürnberg. Deutsche Gesellschaft f. Erd- u. Grundbaue.V., S. 603-626

2- Ripper, P. (1984). Studie zum Tragverhalten eines Pfahles im radial vorgespannten Boden: Experimentelle Untersuchungen in Sand und Berechnungen nach der Methode der finiten Elemente (Published doctoral dissertation), Technischen Hochschule Darmstadt, Darmstadt, Germany.

3- Rau, P. J. (1987). Zum Tragverhalten Biegeweicherrohre im Boden (Published doctoral dissertation), Technischen Hochschule Darmstadt, Darmstadt, Germany.

10.8 Other relevant information

As mentioned above, the experimental hall of TUDa has the following dimensions: 23 m x 23 m x 7 m (L x W x H) (Figure 80). Entry door is currently 3.6 m x 2.87 m (W x H), but there is a plan to increase the height to 4.5 m in order to allow bigger vehicle to drive inside the hall. The hall is equipped with a crane with a maximum capacity of 5 t.

The workshop of TUDa can construct additional designs that may be required by the experiments. Regarding the type of information that can be delivered to the Users, data plots/interpretation can be provided in addition to raw data.

Figure 80 Overview of the TUDa experimental hall

11 CEDEX Track Box (CEDEX)

11.1 Basic information

Table 29 collects some basic information about the facility.

Table 29 Basic information of CEDEX Track Box

CEDEX TRACK BOX (CTB)	
Name (short)	CTB
Name (long)	CEDEX Track Box
Owner	CEDEX
Location (City/Country)	Madrid/Spain
Address	C/ Alfonso XII 3, 28014
Website (vernacular language)	http://www.cedex.es/CEDEX/LANG_CASTELLANO/ORGANISMO/CENTYLAB/LG/LINEAS/trackbox.htm
Website (English)	http://www.cedex.es/NR/rdonlyres/D3AAEA4F-4E44-4194-B761-E0B760D2CF98/144152/CEDEXTRACKBOX_english.pdf
Contact (e-mail)	Jose.Estaire@cedex.es
Head of facility (name/e-mail)	José Estaire / Jose.Estaire@cedex.es
Construction year	2004

11.2 Scope of the facility

CEDEX Track Box is a testing facility mainly developed for studying the geotechnical behavior of the railway infrastructure, composed by the track bed layers (ballast, sub-ballast, form layer, prepared subgrade) and the embankment. The facility allows testing models at 1:1 scale. The tests performed make it possible:

- Analysis of short and long term behaviour of the components of railway tracks submitted to any kind of train traffic,
- Determination of the response to innovations to be implemented in railway tracks,
- Data collection for calibration of 3D numerical models

11.3 Facility physical description / Technical specifications

The CEDEX Track Box (CTB) is a 21 m long, 5 m wide and 4 m deep facility mainly for testing at 1:1 scale, complete railway track sections of conventional and high speed lines for passenger, freight and mixed traffics, at speeds up to 400 km/h. Figure 81 shows a general view of CEDEX Track Box facility.

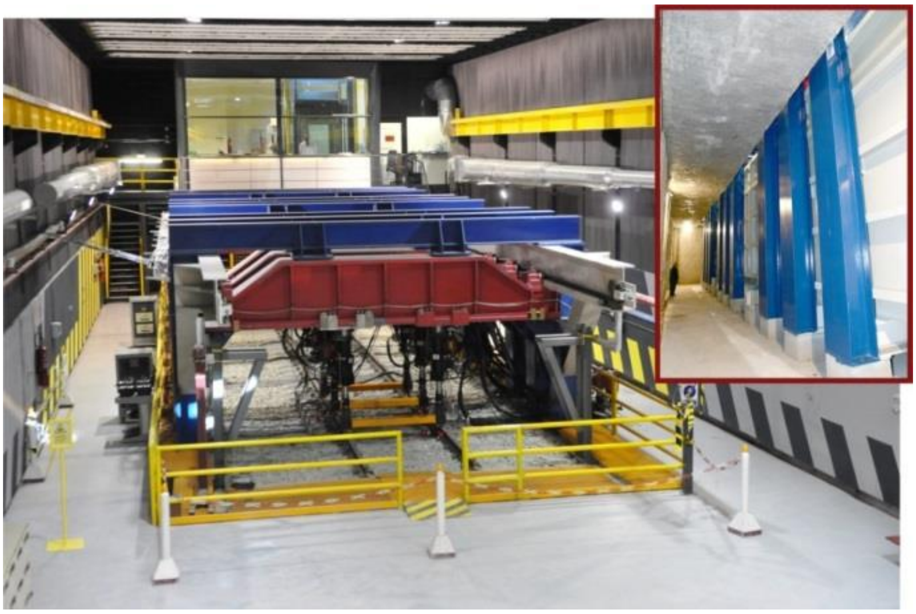

Figure 81 General view of the testing facility

This facility includes in its design the execution of the railway substructure which covers the sub-ballast and form layers and also the embankment zones, as shown in Figure 82.

The CTB length (21 m) it is divided into three zones, each of one can be used for a different railway track design section.

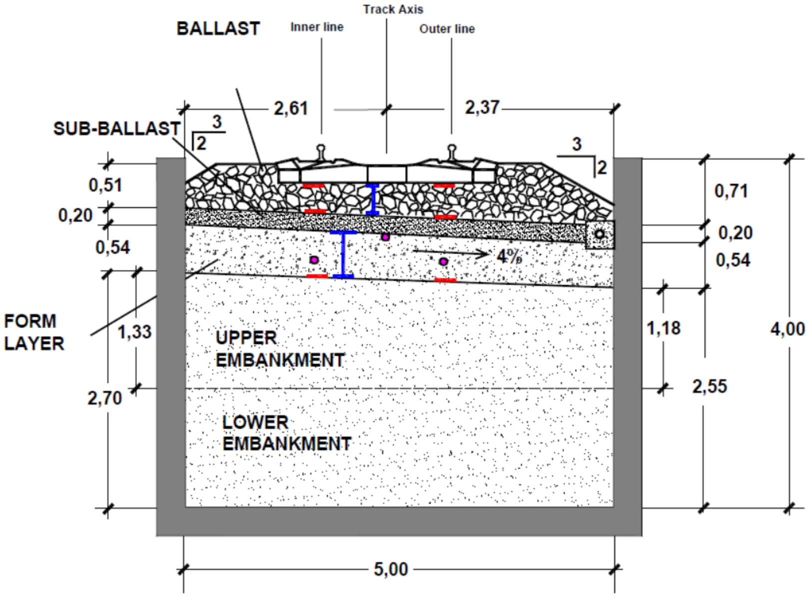

Figure 82 Schematic cross-section of CTB for a particular test

The reproduction of the effect of the approaching, passing-by and going away of a train in a test cross-section, as it occurs in a real track section, is performed by application of loads, adequately unphased, via three pairs of servohydraulic actuators (maximum load of 250 kN at a frequency of 50 Hz). These actuators are placed on each rail at 1.5 m longitudinal separation, as seen in Figure 83. Its principal advantage is the possibility of performing fatigue tests in a fast way as in one working week, the effect of the passing-by of trains during a year in a real section can be modelled.

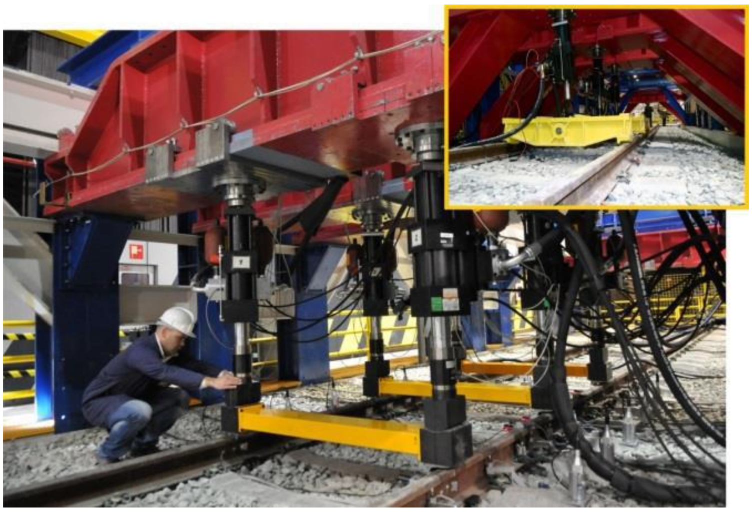

Figure 83 View of the loading system formed by three pairs of hydraulic actuators

The reproduction of track imperfection effects that produce low amplitude high frequency dynamic loads can also be made by the use of two piezoelectric actuators that can apply loads up to 20 kN at 300 Hz.

The railway track response, in terms of displacements, velocities, accelerations and pressures, is collected from a great number of linear variable differential transformers (LVDTs), geophones, accelerometers and pressure cells installed inside both the embankment and the bed layers (ballast, sub-ballast and form layer) of the track. Figure 82 shows a cross section of the testing facility with the position of the sensors used in one of the tests.
On the other hand, the railway superstructure response is recorded with mechanical displacement transducers, laser sensors, geophones and accelerometers installed on the different track components (rail, sleeper and railpad), as seen in Figure 84. The acquisition data unit can receive information from 150 sensors at the same time.

Figure 84 Surface instrumentation installed in one test

11.4 Sensors and instrumentation used in the facility

Table 30 shows the most important aspects of instrumentation used in the CTB facility.

Table 30 Sensor and instrumentation of CTB

Physical magnitude to be measured		**Type of sensor**	**Description**	**Range measurement**	**Accuracy**
Displacement	Relative displacement measurement	LVDT	Inductive displacement transducer	0-10 mm	0,25 %
				0-40 mm	0,50 %
				± 2,5 mm	± 0,010 mm
		Potentiometer	Resistive Transducer	25 mm	± 0,020 mm
	Absolute displacement measurement	Laser system PSD Type	Position Sensitive Device	± 15 mm	± 0,035 mm
Velocity		Geophone	Seismometer	From 1 Hz ± 0.05 Hz (Natural frequency)	
				From 2 Hz ± 0.25 Hz (Natural frequency)	
Acceleration		Accelerometer	Capacitive Accelerometer (1-axis sensing)	From ± 2 g to ± 50 g	± 3 %
				From (0 Hz -400 Hz) to (0 Hz -2000 Hz)	
			MEMS Accelerometers embedded in ballast particles (3-axis sensing)	± 3 g	
				(0 Hz-1600 Hz); X, Y axis (0 Hz-550 Hz); Z axis	
Pressure		Electric stress transducer		(0 - 0,2) N/mm^2	< From 0,1 % to 5 % Full Scale
				(0 - 0,5) N/mm^2	
				(0 – 1) N/mm^2	

11.5 Test description

11.5.1 Type of tests/Problems that can be explored

The tests that can be performed in CTB can have the following features:

- Tests with passenger and freight trains.
- Tests with static loads to determine track stiffness.
- Tests with quasi -static loads to simulate the pass-by of trains at speeds up to 420 km/h.
- Tests with dynamic loads to simulate the effects induced by track irregularities.
- Test to determine the fatigue behaviour of any track component (mainly, fastening system, ballast, subballast) by the simulation of pass-by of millions of axle trains.
- Tests to reproduce the effect of tamping operations on ballast degradation.
- Tests on vibration propagation.
- Tests to determine the lateral and longitudinal track resistance.

11.5.2 Material suitable for the tests

The materials suitable to be tested in CTB are the ones used in the construction of railway tracks:

- Granular material to be part of the ballast layer. It includes natural o synthetic material.
- Material to be part of the sub-ballast layer. It includes natural material, geo-material (geosynthetics) or mixed (e.g. bituminous sub-ballast)
- Embankment construction material, including soils reinforced with geotextiles or treated with lime or cement.
- Slab track, made of concrete
- Prototype of superstructure elements (sleepers, fastening system, under sleeper pad).

11.5.3 Test system limitations and constraints

- The maximum load applied by each pair of servohydraulic actuators is 250 kN at a frequency of 50 Hz.
- The control system limits the maximum speed modelled to 420 km/h.
- The environmental conditions cannot be simulated (e.g. rain, frost, extreme temperatures…).

11.6 Examples of results

11.6.1 Static tests

The measurement of track vertical stiffness in any track condition is made by imposing static loads by the servohydraulic actuators. Figure 85 shows the time-load curve imposed in this kind of static tests. The rail deflection is measured at some points, situated at different distances from the load application point with the aid of laser sensors.

The rail deflection, as a function of the load applied, obtained in the seven measurement points situated in both rails are shown in Figure 85. It can be seen that the deflection curve is non-linear so railway stiffness should always be referred to the load in which it is measured.

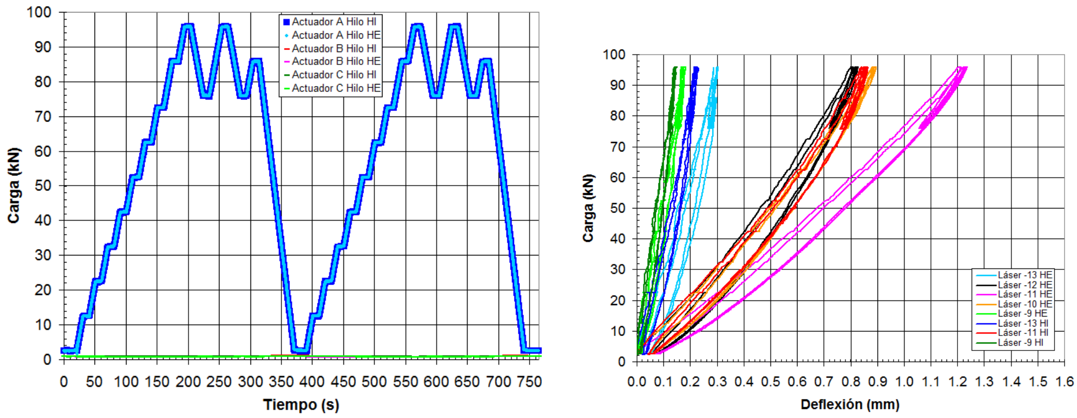

Figure 85 Time-load curve imposed in a static test (left) Deflection curve obtained in a static test (right)

The rail deflections obtained in different points of the rail during three static tests in which the loads were imposed with the three actuators, acting independently, can be seen in Figure 86.

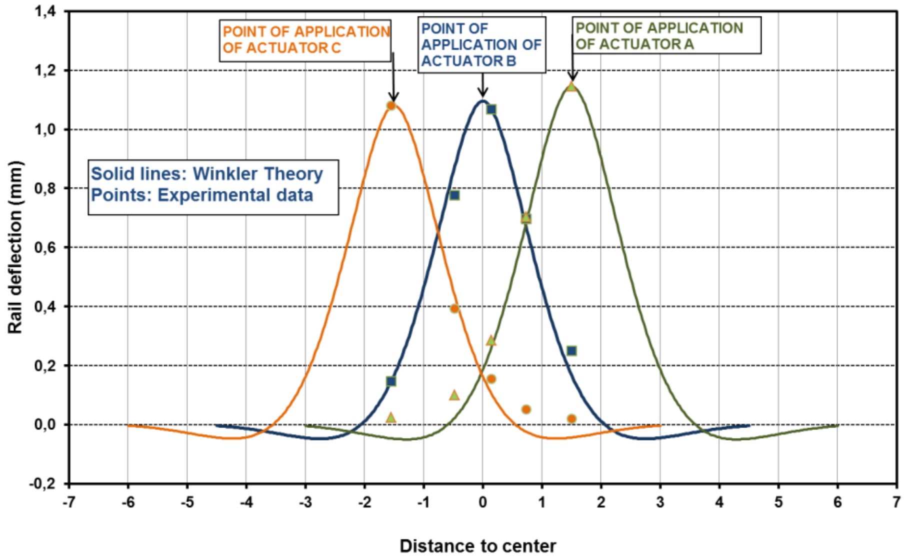

Figure 86 Rail deflection at different points during a set of static tests

The good fitting between the measures and the theory, seen in Figure 86 and in a great number of other static tests, proves that the rail deflections due to a vertical single load can be predicted with high accuracy assuming the rail track has a Winkler-type behavior.

11.6.2 Determination of track lateral stability

The study of the track lateral stability can also be carried out in CEDEX Track Box with the aid of a special tool that pushes away the sleeper while its horizontal movement is recorded.
The measurement equipment installed consisted of a load cell, two laser systems (to record the sleeper horizontal movement) and two potentiometers (to control the relative displacement between the sleeper and the rail).
An example of test results is showed in Figure 87, where the peak horizontal load of 12,5 kN was reached when horizontal sleeper displacement was about 2,5 and 1,2 mm.

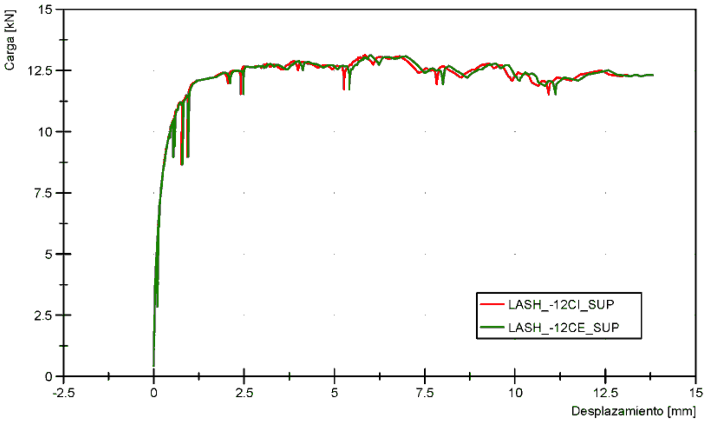

Figure 87 Result of the test performed with the sleeper on clean ballast

The results obtained in these tests show similar shapes and results than Single Tie Push Tests (STPT) performed in real railways in similar track conditions by Samavedam et al. (1999).
Moreover, the track lateral stability tests can be numerically modelled taking into account the following three mechanisms: the friction in the sleeper base with the ballast, the friction in the sleeper lateral faces with the ballast and the passive and active resistances of ballast in the sleeper shoulders (Kish, 2011).

11.6.3 Fatigue tests

Several fatigue tests have been performed in CTB since its construction, each one applying at least one million axles. These tests were carried out under different test conditions:

- Two types of trains: passenger trains (with speeds between 300 and 320 km/h and axle loads mainly between 165 and 190 kN) and freight trains (running at a speed of 120 km/h and axle loads in the range between 220 and 245 kN), as seen in Figure 88
- Two different types of sub-ballast layer: granular, with a thickness of 20 and 30 cm, and bituminous, with thickness of 8, 12 and 16 cm.
- Two different types of track systems: a) GIF AI-99 sleepers with a weight of 3.44 kN and rail pads with a stiffness of 100 kN/mm and b) B90.2 sleepers with a weight of 6.10 kN, equipped with an G04 (SLN 1010) type USP with 0.1 N/mm^3 of static bedding modulus and rail pads with a stiffness of 450 kN/mm.
- Two different situations in the ballast layer: clean and fouled with desert sand in different proportions between 0 and 100%.
- The thickness of the ballast layer was 35 cm in all the tests, being formed by andesite particles.

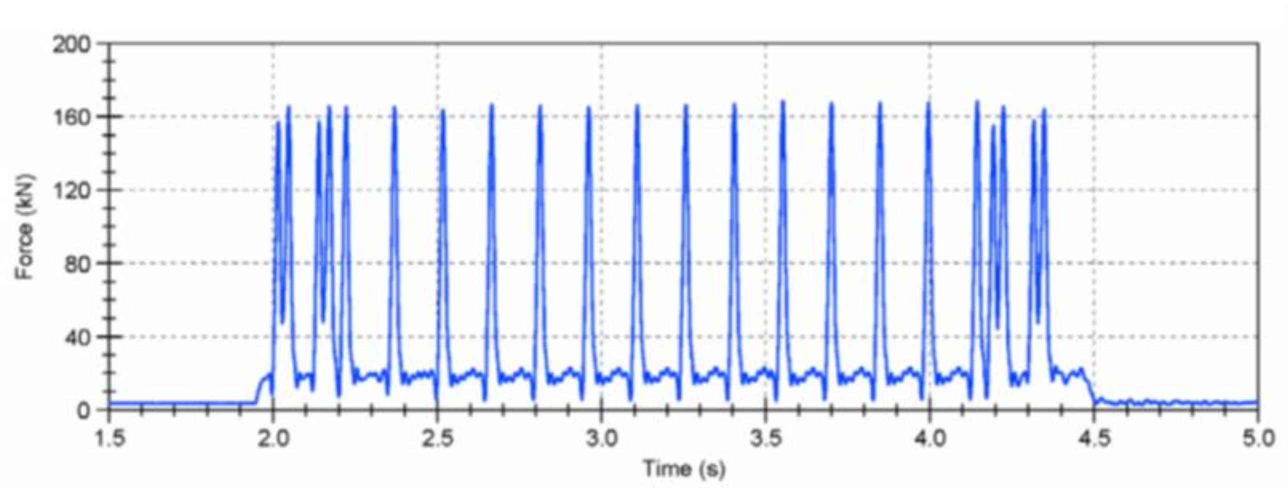

Figure 88 Load-time signal used to simulate the pass-by of S112 Talgo train at 320 km/h

In these tests, permanent settlement curves for the ballast, sub-ballast and form layers were obtained.

The set of the settlement curves obtained for the ballast layer in the tests performed, such as the ones shown in Figure 89 were analysed to discriminate the main factors that have influence in the track settlement and to obtain a mathematical expression to fit the results (Estaire et al. 2017).

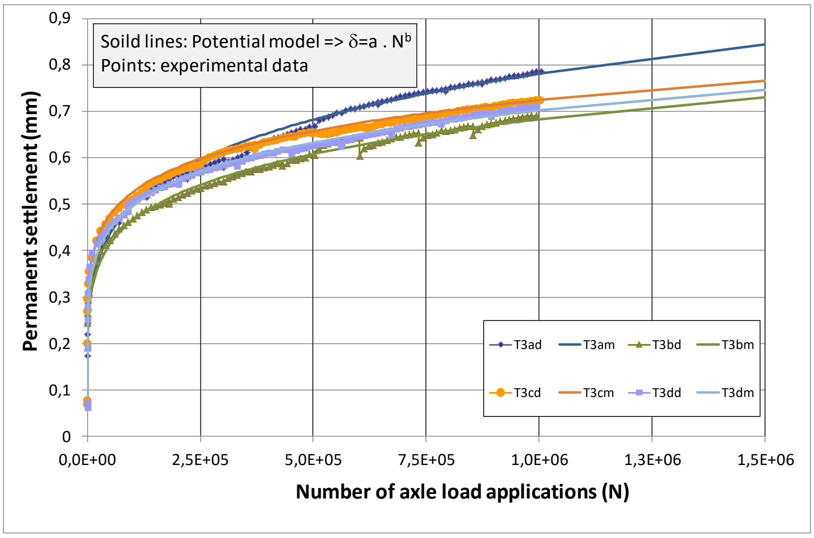

Figure 89 Some ballast settlement curves and their modelling with a potential model

The principal aspects that can be highlighted from the analysis of the experimental curves and their numerical modelling are:

- The values of the permanent settlement obtained in the tests are, in average, around 1 mm in the ballast layers, 0.03 mm in the bituminous sub-ballast layers and 0.02 mm in the form layers for 1 million of load axles, regardless the speed of the trains and the axle loads applied.
- The ballast settlement curves were modelled using a potential expression (δ = a . N^b), in which "a" represents theoretically the permanent settlement in the first cycle and "b" the rate of settlement growth with the number of axles applied. From a conceptual point of view, parameter "a" can be related with the axle load and parameter "b" with train speed, although in the final expression (Eq.2) train speed does not appear as external parameter.
- This model is different of the settlement models existing in literature, as shown with the review performed.
- A remarkable good adjustment of the test curves was obtained that confirms the validity of the potential model.

The summary of the analysis performed for train speeds between 120 and 320 km/h leads to the following general expression of the ballast settlement law, as a function of the number of axle load applications (N), which is considered valid for axle loads (Q) between 110 and 250 kN:

$$\delta\ [mm] = \frac{Q\ [kN]}{25\ K[kN\ /mm]}\ N^{0.165}$$

being Q the axle load, K the track stiffness and N the number of load cycles

11.7 Relevant projects performed in the facility

The most relevant European projects performed in the facility are:

- **SUPERTRACK** (2001-2005): CORDIS | European Commission (europa.eu)

  Experience with high-speed train in recent years has demonstrated unexpected settlement problems at certain sections of railway lines. This has caused railway companies expensive maintenance work and has become a concern in expanding high speed services which provide effective and environment-friendly transportation. The objectives of the project are: i) improving performance of railway ballasted tracks and reducing maintenance costs by understanding the dynamic and long-term behaviour of ballast using large-scale laboratory tests, ii) identifying weak portions of the railway network for retrofitting these locations by innovative, cost-effective methods without interrupting train operation, iii) devising a global numerical model accounting for train-track interaction and non-linear behaviour of track components for a more reliable and cost-effective design.

- **INNOTRACK** (2005-2009): Final Report Summary - INNOTRACK (Innovative Track Systems) | Report Summary | INNOTRACK | FP6 | CORDIS | European Commission (europa.eu)

  The INNOTRACK project concentrated on research issues that contribute to the reduction of rail infrastructure life cycle cost (LCC). The main objective of INNOTRACK has been to reduce the LCC, while improving the reliability, availability, maintainability and safety (RAMS) characteristics. INNOTRACK has been a unique opportunity bringing together rail infrastructure managers (IM) and industry suppliers, the two major players in the rail industry. One of the biggest challenges for railways in Europe is that track costs, the major cost component for infrastructure managers (IMs), have not significantly decreased in the last 30 years. Therefore, the main objective for INNOTRACK is to reduce costs, decrease disturbances and increase availability. In addition to the issues of cost and availability, also noise pollution has become a crucial issue for railway operations.

- **RIVAS** (2009-2013): www.rivas-project.eu (rivas-project.eu)

  RIVAS aims at reducing the environmental impact of ground-borne vibration from rail traffic while safeguarding the commercial competitiveness of the railway sector. For several areas of concern, vibration should be reduced to the threshold of annoyance or even below. The project's goal is therefore to provide tools to solve vibration problems for surface lines by 2013. It therefore aims to contribute to the development of relevant and leading technologies for efficient control of people's exposure to vibration and vibration-induced noise caused by rail traffic.

- **FASTRACK**(2013-2014): FASTRACK

  The main objective of FASTRACK Project is the development of a new system of slab track, focused on High Speed Lines (speed above 250 km/h). To do so, the Project will provide some innovations in design and materials to make it possible the new slab track system to:
    - Get a fast work in place with higher construction efficiencies
    - Need low maintenance which will increase the working hours of the infrastructure
    - Require easy and fast reparation operations to avoid long railway cuts.
    - Reduce the Life Cycle Cost.

- **C4R** (2013-2017): http://www.capacity4rail.eu

CAPACITY4RAIL aims at paving the way for the future railway system, delivering coherent, demonstrated, innovative and sustainable solutions for:

- Track design: transversal approach for infrastructure solutions for conventional mixed traffic and very high speed, integrated monitoring and power supply, reduced maintenance, new concept for highly reliable switches and crossings.
- Freight: longer trains, lower tare loads, automatic coupling, enhanced braking, modern, automated, intelligent, fully integrated system for efficient, reliable and profitable freight operations
- Operation and capacity: traffic capacity computation for freight and passenger, models and simulators for planners: capacity generation, traffic flow, resilience to perturbations, ability to recover from disturbance, computerized real time information to customers and operators at any time
- Advanced monitoring: Integration of Advanced Monitoring Technologies in the design and building process, for an easier-to-monitor (self-monitoring) infrastructure with low cost and low impact inspection. The full sustainability of the developed solutions and innovations will be assessed and scenarios for a smooth migration of the system from its current to its future state will be evaluated

11.8 Reference papers

1- Spectral Analysis of Surface Waves (SASW) as a tool to determine the critical speed of railway tracks. José Estaire & Inés Crespo-Chacón. In Research Gate

2- Proof of critical speed of high speed rail underlain by stratified media. Eduardo Kausel, José Estaire & Inés Crespo-Chacón. Proceedings – The Royal Society. A 476: 20200083. http://dx.doi.org/10.1098/rspa.2020.0083

3- Test results of the friction resistance in the sleeper-ballast contact. María Santana and José Estaire. XVII European Conf. on Soil Mechanics and Geotechnical Engineering. Reykjavik (Iceland). September 2019.

4- Railway track design optimisation for enhanced performance at very high speeds: experimental measurements and computational estimations.Patrícia Ferreira, Rui Maciel, José Estaire & Miguel Rodríguez-Plaza. Structure and Infrastructure Engineering, 2018. DOI:10.1080/15732479.2018.1490325

5- Modification of UIC Code 719 “Earthworks and track bed construction for railway lines” according to the principles developed in EN 16907 “Earthworks” and other European EN Standards. José Estaire, María Santana & David Villalmanzo. IV International seminar: Earthworks in Europe. Madrid (Spain), 19-20 April 2018

6- Large direct shear tests performed with fresh ballast. J. Estaire; M. Santana. Symposium on Railroad Ballast Testing and Properties. New Orleans (USA), January, 2018.

7- Testing railway tracks at 1:1 scale at CEDEX Track Box. José Estaire, Vicente Cuéllar & María Santana. 360.Revista de Alta Velocidad, 2018, nº5, pp.191-217

8- Track stiffness in a ballast track fouled with desert sand. Estaire José, Cuéllar Vicente, Santana María. Symposium International GEORAIL 2017

9- Ensayos de resistencia lateral de vía realizados en el Cajón Ferroviario del CEDEX y su modelización. J. Estaire; V. Cuéllar; M. Santana; J.L. Cámara. Revista Geotecnia. Submitted, 2017

10- CEDEX Track Box as an experimental tool to test railway tracks at 1:1 scale. J. Estaire, F. Pardo de Santayana, V. Cuéllar. In Proceedings of the 19th International Conference on Soil Mechanics and Geotechnical Engineering, Seoul 2017.

11.9 Other relevant information

CEDEX Track Box is part of CEDEX (Centro de Estudios y Experimentación de Obras Públicas) that is a research center depending on the Spanish Ministry of Transport, whose main objective is to provide technical assistance, research and dissemination in all technological matters related to the public works and environment.

Since about 2005 the research activity of CEDEX on the field of railway geotechnics has been performed by using four main tools: a) Instrumentation of railway track sections; b) Laboratory testing at the CEDEX Track Box; c) Laboratory testing of materials, using standard Soil Mechanics test devices; and d) Numerical analysis.

12 Geo-Test Sites (NGI)

12.1 Basic information

Table 31 shows basic information about the Norwegian Geo Test Sites.

Table 31 Basic information of Geo Test Sites

Geo Test Sites	
Name (short)	NGTS
Name (long)	Geo-test Sites
Owner	Norwegian Geotechnical Institute (NGI)
Location (City/Country)	Five geo-test sites located in five different locations: 1. **Soft clay** - Onsøy, Fredrikstad municipality, Viken – Norway 2. **Quick clay** - Tiller-Flotten, Trondheim municipality, Trønderlag – Norway 3. **Silt** – Halden - Halden municipality, Viken – Norway 4. **Sand** – Øysand, Melhus municipality, Trønderlag - Norway 5. **Permafrost** – UNIS east site – Svalbard 6. **Snow avalanche test site facility** – Fonnbu-Ryggfonn
Address	NGI – Sognsvn 72, 0855 Oslo, Norway
Website (vernacular language)	http://geotestsite.no/
Website (English)	http://geotestsite.no/
Contact (e-mail)	Thi Minh Hue Le /thi.le@ngi.no
Head of facility (name/e-mail)	Jean-Sebastien L'Heureux / jsl@ngi.no
Construction year	2016 - 2019

12.2 Scope of the facility

The Geo-Test sites (NGTS) research infrastructure managed by the NGI is a national research facility for geotechnical research. The six benchmark test sites are located in Norway and on Svalbard and have been developed as field laboratories for the testing and verification of innovative soil investigation and testing methods. The sites cover the soil conditions of soft clay, quick clay, silt, and sand. As interest for the Arctic areas grows, one of the sites is in permafrost on Svalbard where detection, sampling, in situ testing and laboratory testing of frozen ground present significant challenges. NGI offers in addition a unique full-scale snow avalanche test site (Fonnbu/Ryggfonn) for studying triggering factors, avalanche dynamics and its impact on the design of mitigation measures.

The test sites serve as reference sites for the industry, public authorities, research organizations and academia. The benchmarked data can be used to develop soil material models, new investigation methods, new foundation solutions and advance the state-of-the-art.

There is already a wide cooperation within the geotechnical community in Norway and abroad for the use of the sites. It is hope that Research at the test facility will provide more cost-effective and sustainable solutions within the building and construction, transportation, and energy sectors and to mitigate the effects of climate change.

Various problems can be explored at these sites include (but are not limited to):

- Testing and benchmarking of in situ investigation/testing methods and instrumentations (CPTU, sampling methods, nonintrusive tomographical methods…etc.)
- Field testing of foundation prototypes (monopiles, suction bucket, energy piles…etc.). See, for example, a

full-scale test of pile capacity in Figure 90.

- Field testing of soil-structure interaction (piles, retaining wall, fill, cut…etc.). See, for example, a full-scale test of a fill for road construction in Norway in Figure 91.
- Experiments for collecting geotechnical parameters to validate constitutive/numerical models (soil-structure interactions…etc.).
- Full-scale testing of snow avalanches and safety measures (dams, screens). See Figure 92.

Figure 90 Full-scale testing of pile capacity in a geo-test site

Figure 91 Full-scale testing of a fill in a geo-test site in Norway

Figure 92 Monitoring from the opposite mountain top av Ruggfonn during testing of triggering snow avalanche

12.3 Facility physical description / Technical specifications

Figure 93 shows the geographical location of the five GeoTest Sites (NGTS). Two of the sites are located in southeastern Norway; the soft clay site in Onsøy and the silt site in Halden. The quick clay and sand sites are situated in mid-Norway, close to Trondheim. The permafrost site is located on Svalbard near the University Centre (UNIS) in Longyearbyen. The snow avalanche facility is situated near Stryn on the west coast of Norway.

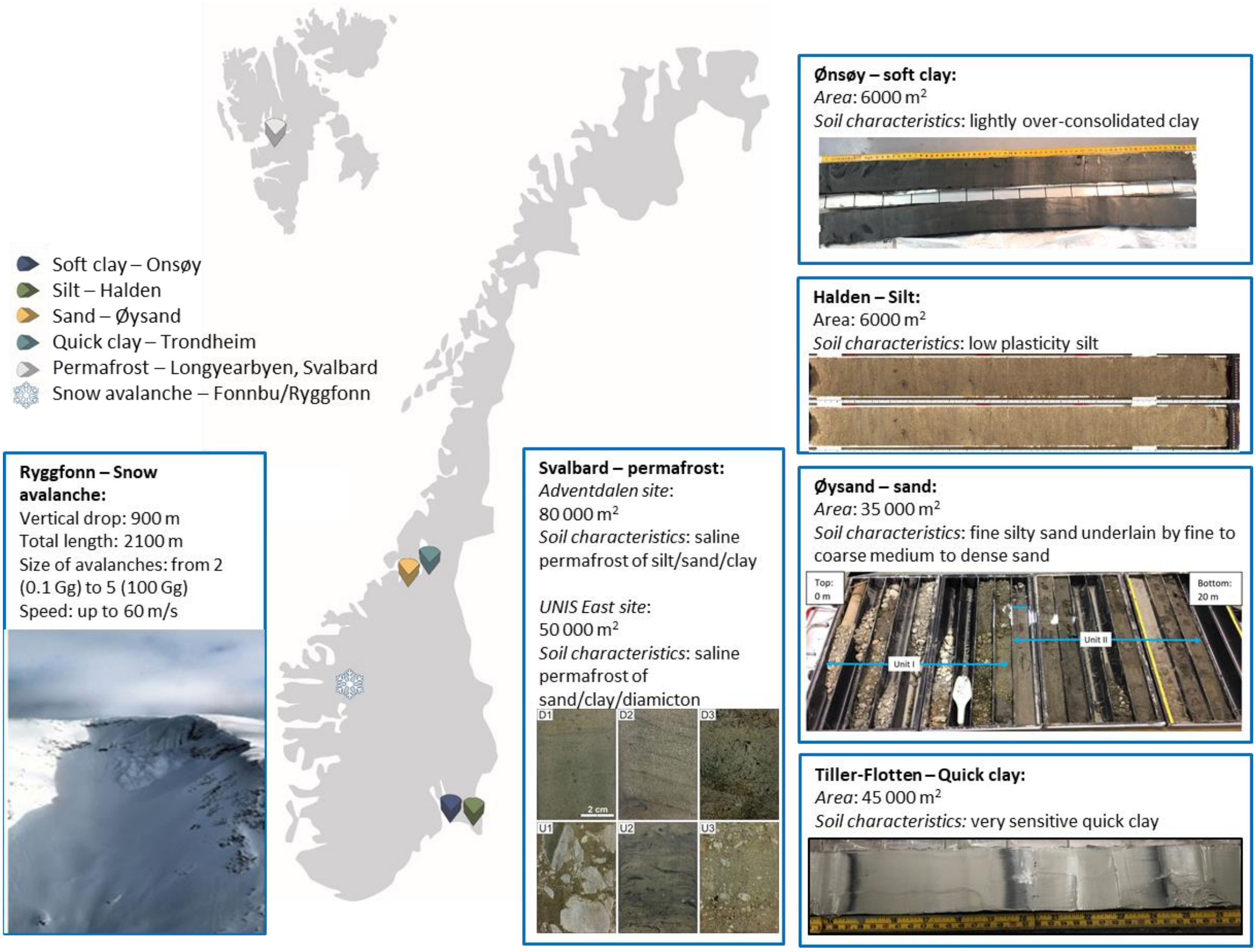

Figure 93 Location of the NGTS geotechnical research sites in Norway

1. **Soft Clay Site – Onsøy**. The soils at the Onsøy site are marine clays. The engineering properties of the Onsøy clay site have previously been documented extensively (Gundersen et al. 2019). The natural water content varies between 45 and 65%. The average plasticity index varies from about 50 in the upper 9m to about 30 below 9m. The sensitivity (St) measured by fall cone tests is constant at about 6. The over-consolidation ratio (OCR) decreases from about 4 near the surface to 1.2 at 30 m depth. Such clays are found extensively in the Northern hemisphere, but also in Japan and southeast Asia. The Onsøy clay is also remarkably similar to clays found offshore at e.g. the Troll, Gjøa, Luva and Aasta Hansteen oil and gas fields. The similarities in characteristic and behaviour with many clays around the world illustrate the significance of the Onsøy deposit as a benchmark site.

2. **Quick Clay Site – Tiller**. Deposits of sensitive marine clay can be found over large areas of Scandinavia and north America. Such deposits are extremely challenging to work with for geotechnical engineers. In addition, landslides occur frequently due to both natural and man-induced triggers. The site at Tiller-Flotten is composed of homogenous marine clay, defined as quick (remoulded strength less than 0.5 kPa) from 7m below terrain and until a depth of 25m. The sensitivity (St) of the clay is about 150. A full overview of the site and data available is presented in L'Heureux et al. (2019).

3. **Silt Site – Halden.** The Halden silt site is located in southeastern Norway, approximately 120 km south of Oslo. The deposit consists of a uniform marine silt up to 10 m thick. Such intermediate soils are challenging materials in geotechnical design. The natural water content (w) in the silt decreases only slightly between depths of 4.5 to 11m, with values at about 30%. From 11 to 15m, the water content decreases more rapidly to about 21%. Soil classification charts suggest the Halden silt to be in the zones at the interface between "transitional soil" and "silt and low rigidity index ' Ir ' clays. Classification tests in the laboratory indicate a low plasticity silt with bulky grains.

The clay content in the silt varies slightly from 9 to 15%. A full overview of the Halden silt site facility is presented in Blaker et al. (2019).

4. **Sand Site – Øysand**. The NGTS facility includes a site with loose to medium dense sand near Trondheim at Øysand. The glaciofluvial and deltaic deposit at this site is approximately 20-25 m thick, relatively homogenous, and consists mostly of fine to medium uniform sand with predominance of quartz minerals, some plagioclase and micas. A full overview of the sand site facility is presented in Quinteros et al. (2019).

5. **Permafrost Sites – Svalbard**. There are two permafrost sites available for testing in Longyearbyen on Svalbard (Gilbert et al. 2019). These sites are included within the NGTS infrastructure to investigate topics including foundation methodology, site investigation techniques, embankment behavior, and artificial cooling systems in saline marine clays and intermediate permafrost soils. These sites were selected as they are representative of the soil conditions in Svalbard and other Arctic locations. Access to both sites is easy as they are located close the the University research centre (UNIS) on Svalbard.

6. **Snow avalanche facility** – **Fonnbu/Ryggfonn**. Fonnbu has, since its inception in 1973, been used for the collection of baseline data on weather and snow conditions, and for the monitoring of avalanches in the area. Fonnbu is located near the full-scale experimental avalanche facility, Ryggfonn, which is also located in the Grasdalen valley. Fonnbu is therefore used to accommodate personnel and serves as a starting point for field tests. Ryggfonn is one of the few full-scale avalanche paths in the world instrumented for full scale experiments. The avalanche path in Ryggfonn has a vertical drop of 900 m and a total length of about 2100 m. The size of the avalanches usually varies from 2 (0.1 Gg) to 5 (100 Gg) measured in the Canadian classification for avalanche and the avalanche speed can reach up to 60 m/s. More information about the snow avalanche facility can be found here: https://www.ngi.no/eng/Services/Technical-expertise/Avalanches/Fonnbu.

12.4 Equipment and instrumentation used in the facility

12.4.1 Permanent installation and instrumentation at the site

Permanent installation and instrumentation at all NGTS test sites include:

- Access road, water and electricity
- Work shelter which can be used as local office and lab
- Weather station
- Thermistor strings for continuous monitoring of ground temperature
- Piezometer for continuous monitoring of porewater pressure

In addition, the snow avalanche facility at Fonnbu / Ryggfonn is equipped and instrumented to monitor real time avalanche behavior in the slide path path, and thereby provides valuable data about the forces and pressure generated, and the velocity of the avalanche. The fixed instrumentation includes LED sensors, load cells and geophones mounted on steel masts and concrete constructions along the avalanche path, as well as in embankment rampart. During field tests measurements with lasers and doppler radar measurements are made.

12.4.2 Available equipment and instrumentation

The NGTS facility provide easy access to well-characterized and documented field test sites for advancing the state of the art in areas such as in situ testing, instrumentation, prediction of soil behaviour, and foundation prototype testing. A comprehensive and high-quality soil database is available for all NGTS test sites. The database includes information from in situ geotechnical tests, geophysical tests and laboratory test as shown in Table 32 and Table 33. Some of the tests are material specific and have not been performed on all sites. Additional tests can be performed upon request. For more information, and for a full overview of the data and equipment available at the

NGTS facility, the reader is referred to L'Heureux et al. (2019), Quinteros et al. (2019), Gundersen et al. (2019), Blaker et al. (2019) and Gilbert et al. (2019).

Table 32 Summary of in situ data available at the Geo-test sites.

Testing methods in the field		Abbreviation
	Cone penetrometer also with resistivity and seismic modules	CPTU, RCPTU, SCPTU
	Dilatometer and Seismic dilatometer	DMT, SDMT
	Push-in-pressure cells	–
	Piezometers	P
	Field vane test	FV
	Rotary pressure soundings	RP
	Hydraulic fracture test	
	Screw plate load test	SPLT
In situ tests	Self-boring pressuremeter test	SBPT
	Geonor (φ 72 mm) fixed piston	–
	Geonor (φ 54 mm) fixed piston (composite)	–
	Sherbrooke block (φ 250 mm)	–
Sampling	Mini-block (φ 160 mm)	–
	Multiple analysis of surface waves	MASW
	Electrical resistivity tomography	ERT
Geophysics	Ground penetrating radar	GPR

Table 33 Summary laboratory data available at the Geo-test sites

Testing methods in the laboratory	
Water content analysis (WC)	Multi sensor core logging (MSCL) including gamma density and magnetic susceptibility (MS)
Unit weight (density)	Split core imaging
Unit weight of solid particles	Oedometer tests at constant rate of strain (CRS)
Atterberg limits	Hydraulic conductivity
Grain size distribution (GSD)	Triaxial - Anisotropically consolidated undrained compression tests (CAUC)
Fall cone test (FC)	Triaxial - Anisotropically consolidated undrained extension tests (CAUE)
Salinity	Direct simple shear (DSS)
X-ray diffraction (XRD)	Bender element test
X-ray inspection (XRI)	Scanning Electron Microscopy (SEM)
Unconfined compression tests (UC)	

12.4.3 Data management

All work carried out at the NGTS facility is available through the Datamap application at http://www.geocalcs.com/datamap. Information from these sites includes results from field and laboratory tests, published articles and reports. Access to the dataset can be accomplished in two steps. First, users register with the system at http://www.geocalcs.com/datamap by creating a username and password. Once logged in, the user navigates to the "Join Project" tab by first clicking the "My Projects" link in the upper right-hand corner of the map viewing screen. They then, must enter the details in Table 34 and click on the "Join Project" button. Users can then navigate back to the Map view by clicking a link in the upper right corner.

Table 34. Access codes and project names to access data from Norwegian geotechnical research sites in the Datamap application.

Site	Soil type	Operator	Project name	Project code	Reference(s)
Onsøy	Lightly OC marine clay	NGI	NGTS-Clay	NGTS2016	Gundersen et al. 2019
Halden	Silt, clayey silt	NGI	NGTS-silt	NGTS2016	Blaker et al. 2019
Øysand	Gravelly sand to silty sand	NGI	NGTS-Sand	NGTS2016	Quinteros et al. 2019
Tiller-Flotten	Very sensitive clay	NGI/NTNU	NGTS-Quick_clay	NGTS2016	L'Heureux et al. 2019
Longyearbyen	Permafrost	NGI/UNIS	NGTS-Permafrost	NGTS2016	Gilbert et al. 2019

12.5 Test description

12.5.1 Type of tests/Problems that can be explored

The NGTS infrastructure is a geotechnically well-documented arena for the entire geotechnical community for basic and applied research and education on soil testing, soil behavior and calibration of foundation design methods. The availability of the sites, the high-quality database and the established facility has already led to its use for e.g. large-scale testing and for verification of investigation techniques. Example of tests and problems earlier performed at the NGTS facility includes:

1. Benchmarking of soil investigation methods on- and off-shore applications (e.g. CPTU, T-ball, SDMT, sampling tools, etc.)
2. Testing of new instrumentation and monitoring technology (e.g. sensors)
3. Field testing of various foundation prototype (e.g. pile capacity tests, testing of suction anchors, etc.)
4. Investigation of soil-structure interaction and comparison of field/lab measurement and numerical models (e.g. piles, sheetpiles, retaining wall, anchors, excavation, slopes, embankment, etc.)
5. Testing of new and innovative soil stabilisation methods (lime-cement, bioash, biocementation, salt, etc.)
6. Permafrost related problems in a changing climate (e.g. foundation methodology in frozen soils, artificial cooling systems, solifluction and creep related problems, etc.)
7. Snow avalanche related problems (design and test of mitigation measures, sensors and early warning systems, etc.)

12.5.2 Test system limitations and constraints

Site conditions at the NGTS facility can vary depending on seasons due to variation in temperature, ground cover, natural variation of groundwater table. Testing can be difficult to perform in wintertime due to cold temperatures and lack of natural light. One should be aware that ground conditions have natural variations in groundwater and geology at each geo-test sites.

12.6 Examples of relevant projects and results

Testing and verification of installation methods for stabilization of quick clay with salt
This project tested the impact of various salt installation procedures on excess pore pressure generation in the sensitive ground. The benefit-cost factors related to these procedures were found to be small compared to conventional landslide mitigation measures. Base on the results, guidelines for safe and cost-efficient installation

procedures were proposed by using potassium-chloride as a sustainable landslide mitigation-measure in slopes with highly sensitive quick-clay deposits. A full overview of the study and results is presented in Eide Helle et al. (Submitted).

Figure 94 Installation of salt injection well for stabilization of quick clay in Tiller-Flotten

Effect of freezing thawing cycle on slope stability in Øysand (Shin et al. 2020). This work included a full-scale man-made slope brought to failure at the Øysand site. A remote monitoring system was installed on the slope to observe its behavior against the governing factors of slope stability in cold region.

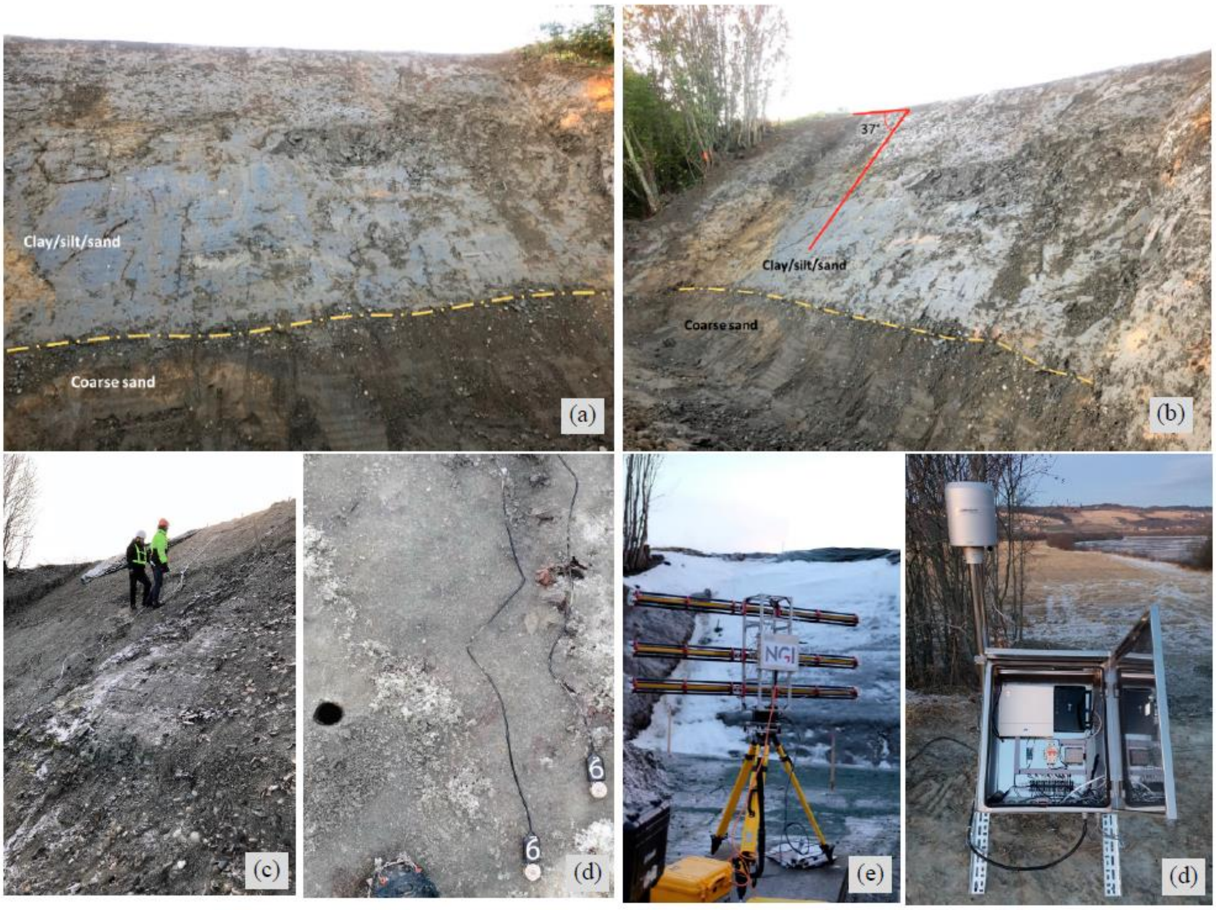

Figure 95 Test slope at Øysand geo-test site.

(19 37 degree man-made test slope (b) Layers of test slope (c) Inclinometer installations (d) MPS-6 sensors (e) Lidar system (f) data logger box

Impact of cone penetrometer type on measured CPTU parameters

This project investigated the repeatability of CPTU measurements conducted in different types of soil to investigate if recent advancements in cone design and electronics have led to improved repeatability and less scatter in CPTU data. Eight different cone penetrometers from five manufacturers have been used in comparative testing program at the various NGTS sites. Up to four tests were carried out with each cone type and the results have been systematically compared. For all of the cones, penetration pore pressure u2 gave the most repeatable results.

Repeatability for sleeve friction, fs, readings, was not always good, which is in line with previous experience. Hence, one should be careful with using this parameter, and also the friction ratio, when interpreting soil parameters for design. Results show that the u2 values appear to frequently be the most reliable parameter and should be used in addition to qt for deriving soil parameters. A summary of the results and findings can be found in Lunne (2018).

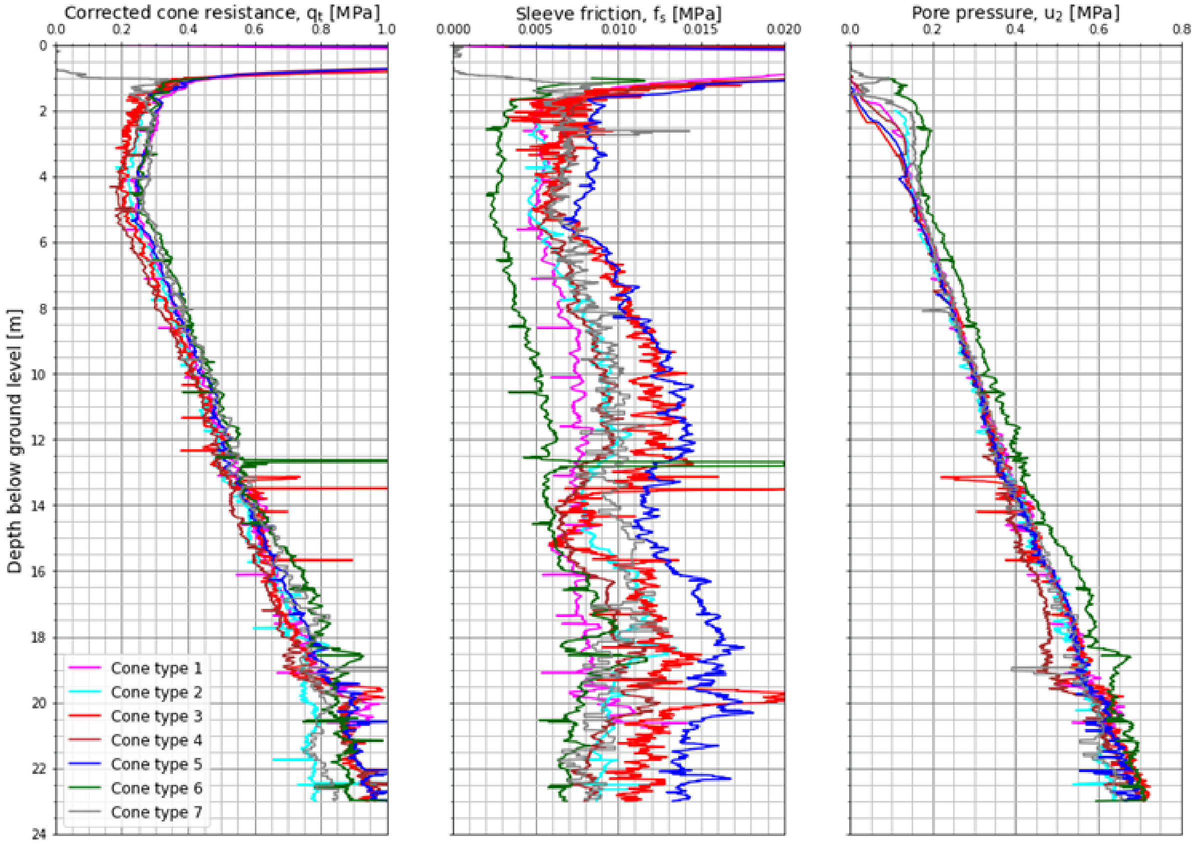

Figure 96 Measured CPTU parameters from different cone types in Onsøy soft clay site

Other example projects that were performed in the geo-test sites include:

- Foundation concept on plastic clay in Onsøy soft clay site (University of Western Australia)
- CPTU rate effect in Halden silt geo-test site (Univervisty of Massachusett Amherst and NGI)
- Development of flow cone in Halden silt geotest site (Ørsted and NGI)
- Testing of sonic sampler drill in Halden, Øysand and Onsøy geo-test sites (Eijkelkamp)
- Comparison of shear wave velocity measurements (Vs) using MASW with insitu data from seismic penetrometer (SCPTU) and seismic dilatometer (SDMT) in the field (Univ. of Reykjavik, Iceland) (Ólafsdóttir et al. 2019).
- Embankment test at Onsøy (Berre, 2014)
- Development of high-quality soil sampler for offshore applications.
- Full-scale testing of snow avalanche in Ryggfonn
- Testing of measures against snow avalanches (dams, screens)

12.7 Reference papers

1- Gundersen AS, Hansen RC, Lunne T, et al. (2019) Characterization and engineering properties of the NGTS Onsøy soft clay site. AIMS Geosci 5: 665–703.

2- L'Heureux JS, Lindgård A, Emdal A (2019) The Tiller-Flotten research site: Geotechnical characterization of a sensitive clay deposit. AIMS Geosci 5: 831–867.

3- Blaker Ø, Carroll R, Paniagua Lopez AP, et al. (2019) Halden research site: geotechnical characterization of a post glacial silt. AIMS Geosci 5: 184–234.

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