Centrifuge facilities at Technical University of Denmark

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The geotechnical group at the Danish Technical University (DTU) operates a geotechnical beam centrifuge. The centrifuge was built in 1976 and has been upgraded over the years, latest with onboard data acquisition and control systems. The centrifuge concept involves an increased gravity field in which the physical model is placed and tested. The capabilities of the centrifuge at DTU make it possible to obtain a scale factor of 75-85 in the tests which equals a soil volume in prototype scale of ø40m and a depth of 40 m.
The centrifuge facilities at DTU have through the years been used for testing various geotechnical issues, such as suction anchors, tension piles in clay, active earth pressures on sheet piles and group effects for laterally loaded piles.

1 INTRODUCTION

Modelling is an important part of geotechnical engineering and research. The geotechnical engineer is by use of models able to investigate both the serviceability limit state and ultimate limit state in the design process.
Physical modelling within the geotechnical field is among other things governed by complex stress dependent behaviour, especially in soil-structure interaction. This can be taken into account by using field monitoring and full scale models. Full scale model tests have the advantage of the right soil properties and site conditions but can be extensive/expensive and are not always allowed to reach the ultimate limit state, with failure and/or large deformations.
An alternative is the use of centrifuge modelling, where a small scale test is carried out within an increased gravity field. The increased stress level enables modelling of soil behaviour with soil-structure interaction in small samples with the correct stress dependent behaviour.
The centrifuge facilities have through the years been used for various research projects. Examples include studies of suction anchors [11], tension piles in clay [8], active earth pressures on sheet piles [5], [9] and group effects for laterally loaded piles [10], [12]. Current research is focused on behaviour of a laterally loaded pile in sand subject to cyclic loading.
In this paper physical modelling in general is described. The centrifuge facilities at DTU is described with a brief discussion of the applicability of the centrifuge modelling. The paper concludes with practical examples of the use of the centrifuge.

2 MODELLING IN CENTRIFUGE

The key element in centrifuge modelling is a soil sample in a model container placed at the end of a centrifuge arm rotated in a horizontal plane. The rotation creates a radial acceleration field in which the acceleration in a specified point is given by the angular rotation speed (ω) and the distance (r) from the rotational axis, see Figure 1.
The increased gravitational acceleration is described by the gravity scale factor (N) multiplied with Earth's gravity (g).

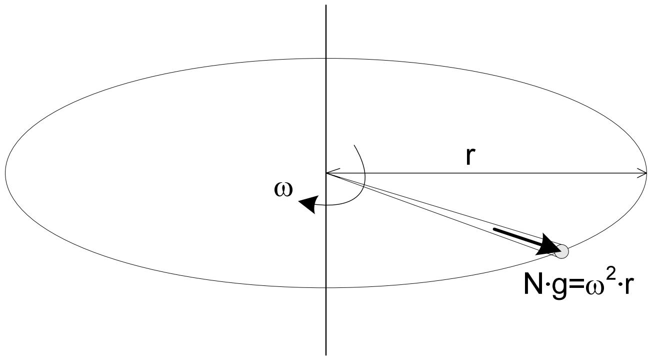

Figure 1 Acceleration by rotation

2.1 Scaling laws

Based on the intention of stress similitude between a model (in centrifuge) and a prototype, the scale factor of linear dimensions (at a given depth) can be derived as shown here:

	Model	**Prototype**
Density	ρ	ρ
Depth in soil	h_m	h_p
Stress in point	$\sigma_m = \rho \cdot N \cdot g \cdot h_m$	$\sigma_p = \rho \cdot g \cdot h_p$
Stress similitude	$\sigma_m = \sigma_p$	
Scaling of linear dimensions	$h_m/h_p = 1/N$	

The scale factors listed in Table 1 can be determined by use of scaling laws. Scaling of time depends on the problem investigated. Diffusion problems (seepage), dynamic problems (inertia) and viscosity problems are not scaled in the same way and it is necessary to consider the mechanisms modelled. The issue is considered in [1] and [2].

Table 1 Scale factors

Parameter		**Unit**	**Scale (model/prototype)**
Acceleration		m/s^2	N
Linear dimension		m	1/N
Stress		kPa	1
Strain		-	1
Density		kg/m^3	1
Mass or Volume		kg or m^3	$1/N^3$
Unit weight		N/m^3	N
Force		N	$1/N^2$
Bending moment		Nm	$1/N^3$
Bending moment / unit width		Nm/m	$1/N^2$
Flexural stiffness / unit width (EI/m)		Nm^2/m	$1/N^3$
Time:	Diffusion	s	N^2
	Inertia	s	N
	Viscous	s	1

2.2 Scaling effects

The gravity scale factor varies linearly with distance from the rotation axis, and with the square of angular rotation speed, see Figure 1. The rotation speed is usually kept constant during centrifuge tests, which leads to a small difference between the stress increase with depth in model and prototype, see Figure 2.

A choice of reference level to 2/3 of model height will minimize the error, which for the majority of the stress profile will be less than 3%, [1].

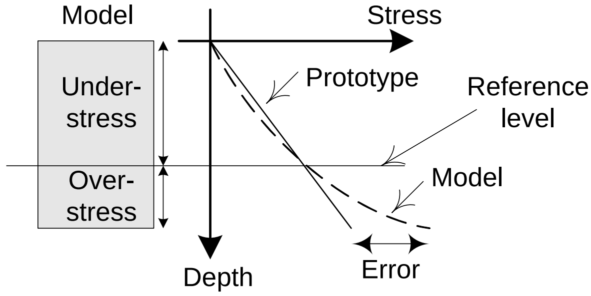

Figure 2 Comparison of vertical stress variation in centrifuge model and corresponding prototype.

If all the linear dimensions in the model should be scaled with the same scale factor, that includes grain size as well. A change in grain size will tend to change the properties of the material in question. It is thus of interest to use the original material, and instead focus on the influence from the particle size on the studied mechanisms. This can be done by using the modelling of models concept with different sized models at different scales used to model the same prototype. Reference [2] considers some cases of modelling of models.

A part of the challenges with scale factors concern the scaling of time when dealing with dynamics and seepage, as introduced in section 2. The dynamic element is scaled by N while the seepage part follows N squared. This issue is usually approached by changing the flow properties of the soil. While the grain size and hydraulic conductivity is kept unchanged, the use of pore fluid with a higher viscosity will solve the scaling problem, [1].

2.3 Practical issues

In addition to the effects mentioned above, boundary effects and physical dimensions need considerations. The fact that the test should be controlled remotely, as the setup is not accessible during the test, should be dealt with as well.

Keeping the challenges in mind, it is though possible to make a manageable model, with respect to size as well as economy, and carry out defined model tests. It is possible to custom fit the setup to analyse specific mechanisms, allow the model to fail or obtain significant deformations, and monitor desired elements.

3 CENTRIFUGE FACILITIES

3.1 Geotechnical centrifuge at DTU.BYG

The geotechnical beam centrifuge at DTU.BYG was built in 1976 and was upgraded in 1998. It has a capacity of 75 g-ton and can provide a gravitational acceleration of 75-85 g. The centrifuge arm is 1.7 m from rotational axis to reference hinge. The U-shaped yoke is 0.93 m high (hence platform radius is 2.63 m). A maximum of 350 kg soil sample and test setup can be applied.

Two sample containers, a circular and a rectangular, are available with the properties listed below. The listed prototype soil volume is based on a gravity scale of 80. One side of the rectangular container is made of Plexiglas which makes it possible to visually monitor the model. The centrifuge has been used for testing sand, clay and limestone samples. Sand samples can be prepared by use of sand rain or spot pouring methods, whereas clay samples either are reconstituted intact clay or kaolin clay, both consolidated according to planned tests by preload or in the centrifuge.

	Circular container	Prototype volume
Diameter	53 cm	42 m
Height	49 cm	39 m

	Box container	Prototype volume
Length	70 cm	56 m
Width	50 cm	40 m
Height	70 cm	56 m

Figure 3 Centrifuge at DTU

3.2 Control and data acquisition system

The centrifuge control and data acquisition system is illustrated in Figure 4. The main feature is the execution of the tests by use of a flight pc located on the centrifuge. The flight pc is remotely controlled from the control room. Electrical slip rings ensure a direct connection to the setup, while the power slip rings provide the necessary power supply to the equipment on the centrifuge (220/380 VAC, 5/10/24 VDC).

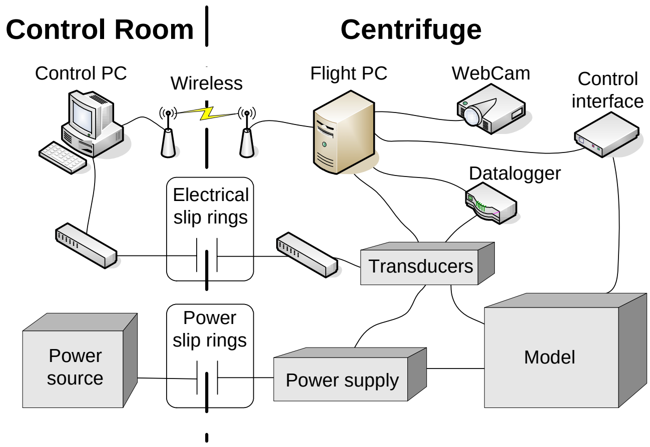

Figure 4 Centrifuge control and data acquisition system

The current setup of the centrifuge allows for connection of 32 transducers (pore pressure, LVDT, etc.) to be logged through the data logger, whereas the flight pc has 16 analogue inputs and 2 analogue outputs, allowing for e.g. 8 transducers and 2 control signals.

4 TEST SETUPS AND SAMPLE RESULTS

The centrifuge has over the years been used for testing various geotechnical issues. Some of the issues are:

- Behaviour of suction anchor in sand – installation and determination of ultimate resistance. [11]
- Negative skin friction on pile and pile groups in clay. [7]
- Tension piles in clay. [8]
- Cone penetration tests in sand and clay with measurement of pore pressure, tip resistance and skin friction. [14]
- Vertical bearing capacity of thin walled profiles. [13]
- Active earth pressure on sheet pile walls in sand. [9] and [5].
- Group effects for laterally loaded piles in sand and clay. [12] and [10]
- Stresses in concrete pipes – pipes placed in soil with applied surface load. [6]

- Laterally loaded pile in sand – large diameter piles exposed to static and cyclic lateral loads.

The following sections show examples of results obtained from tests with cone penetration in sand and laterally loaded pile in dense sand.

4.1 Mini piezocone penetrometer

A small scale piezocone penetrometer is available for centrifuge testing at DTU. The cone has a cross sectional area of 1 cm^2 and can be penetrated 300 mm.See Figure 6.
The objective is to apply the cone for in-flight testing of the prepared soil samples. Sand and clay has been used in various types of tests in the centrifuge.

Table 2 Classification parameters for Fontainebleau sand.

Specific gravity of particles	d_s	2.646
Minimum void ratio	e_{min}	0.548
Maximum void ratio	e_{max}	0.859
Average grain size (mm)	d_{50}	0.18
Uniformity index	U	1.6

Current focus is on testing dry samples of Fontainebleau sand, which is silica sand with the classification parameters listed in Table 2.
A spot pouring hopper is designed and applied for the preparation of sand samples [3]. A relative density, I_d, between 0.50 and 0.95 can be obtained by varying flow rate through nozzle and fall height into the container.
The cone has been applied to perform in-flight soil testing of sand samples. Figure 7 shows measured tip resistance for 3 cone penetration tests in a medium dense sand (I_d =0.55) at a gravitational acceleration of 61 g. The tests are made at different locations in the same sample. The figure includes lines representing the theoretical tip resistance calculated for 4 different values of the friction angle. The tip resistance is calculated according to pile tip resistance in sand [15]:

$$Q_c = 2\sigma_0 N_q A_{tip}$$

σ_0 is vertical effective stress, A_{tip} is tip area and N_q is a bearing capacity factor given as a function of friction angle (φ):

$$N_q = \exp\left(\pi \tan\left(\varphi\right)\right)\frac{1+\sin\left(\varphi\right)}{1-\sin\left(\varphi\right)}$$

It is seen from the 3 CPTs in Figure 7 that the upper part of the present sample is fairly homogenous with respect to strength in both vertical and horizontal direction, whereas some variation is seen in the lower part, with one CPT diverging from the others. The diverging test is located close to the edge of the container, where it might be affected by boundary conditions. The sand is consolidated during gravitational acceleration from 1 g (at rest) to 61 g (level during test), and some effect of friction along the container walls is expected.

Figure 5 Spot pouring hopper for preparation of sand samples.

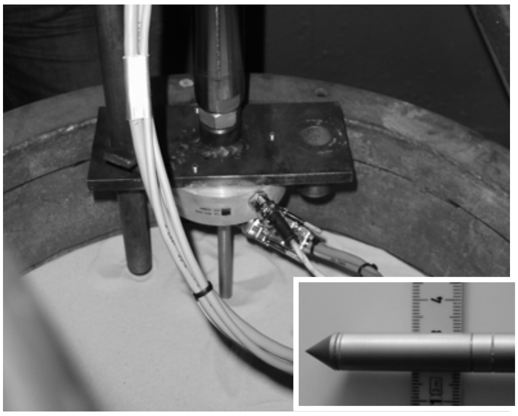

Figure 6 Mini cone penetrometer

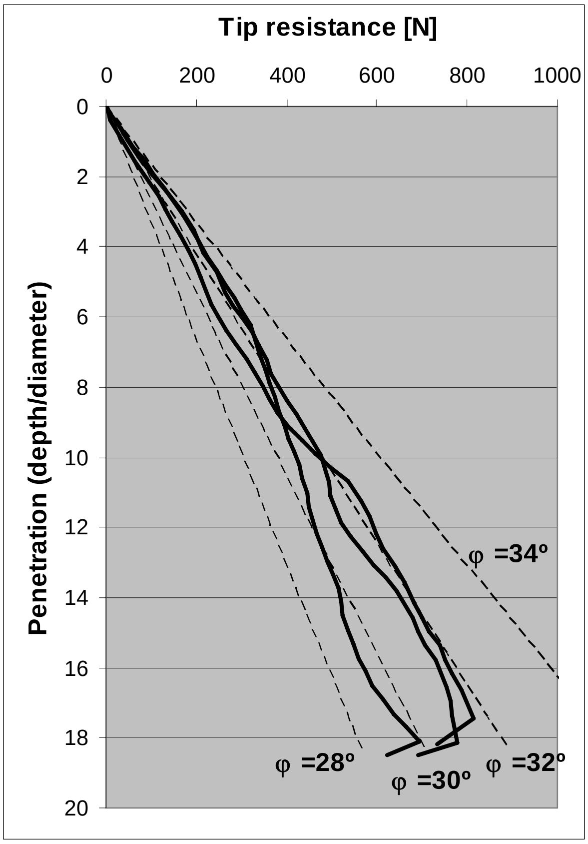

Figure 7 Results from cone penetration test in medium dense sand (I_d= 0.55). Test is at 61g and the results are not scaled.

4.2 Laterally loaded pile in sand

Current research in the centrifuge at DTU is focused on laterally loaded pile in sand subject to cyclic loading. A part of this research involves testing of a series of piles with different diameter and length to diameter ratio. All tests are in very dense Fontainebleau sand - relative density of 0.90-0.95 (classification parameters are listed in section 4.1). The findings from the physical modelling are compared with the theoretical approach based on p-y curves as defined in e.g. [4].

A loading frame for tests on a laterally loaded single pile is illustrated in Figure 8. The frame fits a circular container with a diameter of 53 cm and a height of 49 cm. Each pile is fixed to a slide through a bending beam load cell, either fixed head conditions or connected with a hinge, see Figure 9. Pile head displacement is measured by use of a displacement transducer mounted on the slide.

The tested piles are listed in Table 3, and the load-displacement curves are included in Figure 10.

Table 3 Laterally loaded piles.

Pile	Length in soil (L)	Height of force above surface (H)	Model diameter (D)	Prototype diameter (D)
1	6 D	2.5 D	16 mm	1.0 m
2	8 D	2.5 D	16 mm	1.0 m
3	10 D	2.5 D	16 mm	1.0 m
4	6 D	1.43 D	28 mm	2.0 m

A Winkler model, with linear elastic beam supported by springs defined by API p-y curves (described in e.g. [4]), is set up for each of the above listed tests. Pile 3, 1.0 m diameter and 10D installation length, is used as reference pile to which the Winkler model is calibrated. The calibrated friction angle is 42 degrees and modulus of sub grade reaction, k, is 2700 kPa. The load-displacement curves presented in Figure 10 shows a very good resemblance between theory and tests for the ø1.0 m piles, while some deviation is seen from the test representing a ø2 m pile.
The centrifuge test ø2 m has a higher initial stiffness but a lower bearing capacity than expected from the Winkler model. The measured shape of the load-displacement curve (initial stiffness, bearing capacity and curvature) is not obtained perfectly by the p-y curve formulation and it is necessary to further investigate the differences between the pile diameters.
The remaining part of the test programme will include testing of ø2 m piles with lengths of 8D and 10D, along with cyclic loading of the piles (ø1-2 m and L = 6,8,10 D).

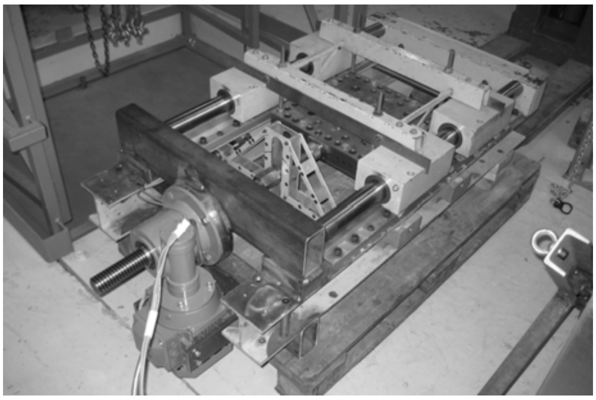

Figure 8 Loading frame.

Figure 9 Bending beam load cell and pile(s).

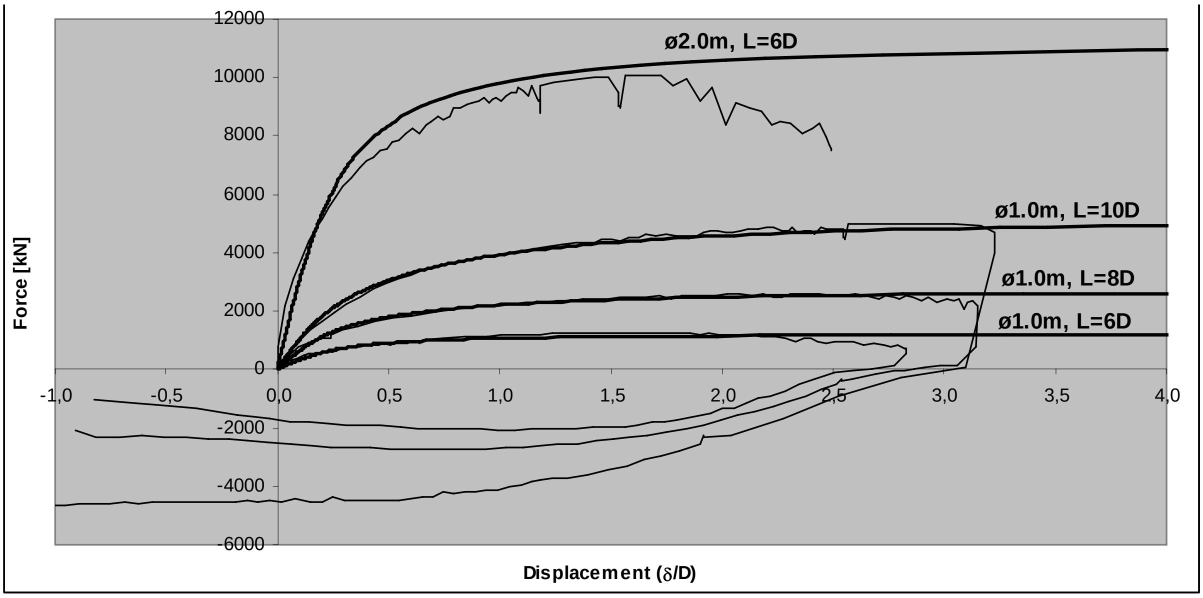

Figure 10 Load-displacement curves for pile tests.

5 CONCLUSION

The presented centrifuge tests illustrate some of the possibilities in the use of physical modelling in centrifuge, including problems concerning stress dependent behaviour, verification of soil properties in-flight and compatibility with analytical formulations.
The centrifuge provides possibilities to carry out tests where the modelled subject is entitled to fail without extensive consequences that normally are connected with destructive testing, e.g. bearing capacity.

6 REFERENCES

1. Taylor, R. N. “Geotechnical Centrifuge Technology”, ISBN 0 7514 0032 7, Blackie Academic & Professional, 1995.
2. Fuglsang, L. D. & Krebs Ovesen, N. “The application of the theory of modelling to centrifuge studies, Centrifuges in Soil Mechanics, 1988, Rotterdam: Balkema.
3. Chen, H.T., Lee, C.J.&Chen, H.W. 1998. The travelling pluviation apparatus for sand specimen preparation. Centrifuge 98. Rotterdam: Balkema.
4. DNV, “Design of offshore wind turbine structures, Offshore Standard DNV-OS-J101”, DNV June 2004.
5. Krogsbøll, A. S. & Fuglsang, L. D. “Physical and numerical modelling of earth pressure on anchored sheet pile walls in sand”, Physical Modelling in Geotechnics – 6th ICPMG ’06, Balkema.
6. Hegnsted, B. & Hansen H.O., “Toglast på rør”, BSc. thesis in Danish, DIAB 1978.
7. Christensen, L. & Mortensen M., “Negativ overflademodstand på pælegrupper”, MSc. thesis in Danish, DTU 1997.
8. Larsen, C.B. & Nielsen, M., “Trækpæleforsøg i ler i centrifuge”, MSc. thesis in Danish, DTU 1991.
9. Schultz, M. & Larsen, C.S., “Jordtryk på bøjelige vægge”, MSc. thesis in Danish, DTU 2003.
10. Brødbæk, C. “Numerical and centrifuge modelling of laterally loaded piles”, MSc. thesis, DTU 2000.
11. Foged, B. “Modelling of suction anchors”, MSc. thesis, DTU 2000.
12. Haahr, F. “Interaktion mellem tværbelastede model pæle i sand (forsøg i centrifuge)”, PhD. thesis in Danish, DTU 1989.
13. Meier, A.B. & Møller, H.S. “Vertickal bæreevne af tyndfligede profiler”, MSc. thesis in Danish, DTU 2004.
14. Petersen, E. & Molnit, T. “Penetrometerforsøg i centrifuge II”, MSc. thesis in Danish, DTU 1992.
15. Hansen, B. “Geoteknik og fundering del 1”. Laboratoriet for fundering Danmarks Tekniske Højskole, 1978. (Danish Textbook)