Concept of Centrifuge Modelling for Geotechnical Studies

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In a rapidly growing urban landscape, the serviceability performance of buildings and infrastructure in tight spaces becomes as critical as its strength performance in design. With the current trend where design is heading towards performance-based, tools which can accurately predict complex soil-structure interaction becomes essential. Centrifuge technology is a powerful and useful means available to geotechnical engineers besides numerical analyses, to study real-life complex soil-structure interaction problems. Centrifuge technology can be applied to several areas within the field of geotechnical engineering, some of which are presented below.

While the failure of a building or infrastructure is considered not so common, the problems of how they deform or how they behave when acted upon by external loads, is becoming a common concern. In an interview with *Jurutera*, Professor Bolton (1) stated that "a safety factor is the ratio between an estimated material resistance or estimated resistance of the structure and the ground in some way where the load is placed upon it. As these two estimated things are somewhat imaginary and because the ratio of them has no particular physical meaning, safety factors cannot be related to observed behaviour."

In cases where means of geotechnical field testing and instrumentation may not be practical, physical models help to idealise the situations and to accurately predict complex soil structure interactions in order to ensure structural performance. Furthermore, while conventional soil mechanics laboratory tests may be useful in helping to characterise certain behaviour and properties of soils and rocks, the limitations of applying the outcomes directly to geotechnical engineering practice (e.g. three-dimensional conditions) can be overcome by physical modelling.

Early works on the use of centrifuge were noted as far back as in 1931 (2) in the USA and 1963 (3) outside of the USA and Russia. These works were related to solving mining and tectonics problems (4, 5). The development of sound principles of geotechnical centrifuge technology in the later years has contributed to a consistent increase in the number of centrifuge facilities around the world, including in the USA, UK, France, Netherlands, Canada, Singapore, Switzerland, China, Taiwan, Korea, Hong Kong and India.

In addition to the increased number, capacity and size, newer centrifuges are being built with specialised features for better measurement of model deformations including in-flight technology to simulate heating, freezing, excavations, surcharge loadings and measurement of soil strength profiles. Currently, centrifuge technology is being used to develop fundamental understanding and to resolve both common and unique problems related to various areas of geotechnical and geo-environmental engineering such as slopes, embankments, excavations, tunnelling, earthquakes, dams, mining, land reclamation and ground improvement.

THEORY OF CENTRIFUGE MODELING

The basic theory of centrifuge modelling depends on the fact that soil behaviour is governed by its natural triangular stress distribution due to the self-weight of the soil body, which is impossible to reproduce in the laboratory over real-life installation depths (e.g. a long pile).

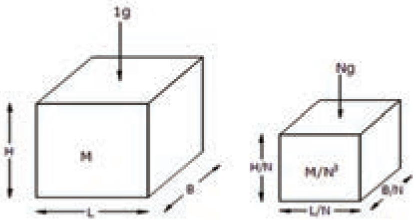

Figure 1: Basic principle of centrifuge modelling [6]

A centrifuge creates "artificial gravity" by spinning a body of soil at a constant radial velocity. This acceleration is usually defined in terms of a multiplier of gravity, or N times Gravity. As such, when increasing the gravitational force applied to the soil body, we are able to achieve similar stress distribution with depth, as experienced by the prototype in the field.

In principle, by revolving a soil body at N times Gravity, the unit stresses in the prototype can be achieved while simultaneously decreasing the scale of the model by the same ratio N (see Figure 1). While the scale of the model needs to be reduced by the ratio N, other analogous scaling laws can also be derived from this for parameters such as unit weight, velocity, force, acceleration etc. Typical scaling laws used in centrifuge modelling are shown in Table 1.

Table 1: Scaling relationships for centrifuge models

PARAMETER	PROTOTYPE (REAL-LIFE DIMENSION)	CENTRIFUGE MODEL AT Ng
Linear dimension	1	1/N
Area	1	$1/N^2$
Volume	1	$1/N^3$
Density	1	1
Mass	1	$1/N^3$
Acceleration	1	1/N
Displacement	1	1/N
Strain	1	1
Energy	1	$1/N^3$
Stress	1	1
Force	1	$1/N^2$
Time (creep)	1	1
Time (dynamics)	1	1/N
Time (seepage)	1	$1/N^2$
Flexural rigidity, EI	1	$1/N^4$
Axial rigidity, EA	1	$1/N^2$
Bending moment	1	$1/N^3$

1. ADVANTAGES AND LIMITATIONS OF CENTRIFUGE MODELLING

As with any tool, there are advantages and limitations when using the centrifuge. One major advantage is its ability to accurately model and predict various problems involving soil media.

Smaller scale models of real-life construction scenarios can be modelled and various types of miniature equipment can be installed. The soil preparation and the consolidation process / history can be controlled so as to simulate real-life situations. Commonly, miniature pore pressure transducers are employed to measure pore pressure development while Linear Variable Displacement Transducers (LVDT) and non-contact laser transducers are used to measure soil surface deformations or foundation movements. A hydraulic cylinder (actuator) is used for any movements required during high-g spinning, such as when carrying out T-bar or vane shear tests, excavation or installation of piles in-flight.

A particularly useful application is the Particle Image Velocimetry (PIV) technique, where flock particles are applied to the front face of the soil model and tracked via a series of images. Small subsets of the photographs are analysed via PIV (7) to see the overall soil movement patterns.

When the time aspect of the models is considered, the particular process that is being considered plays a significant role. For consolidation, the time scales are calculated based on the theory of consolidation by Terazaghi. By applying linear scaling laws to the governing equation for consolidation, the time scale is found to be:

$$\frac{t_{model}}{t_{prototype}} = \frac{1}{N^2} \qquad (1)$$

This suggests that the model consolidation rate is N^2 times faster than the prototype, which can be a major advantage in modelling many soil mechanics problems. For example, a soil sample which takes 3 years to achieve 95% consolidation could finish consolidation within 10.5 hours at 50g in the centrifuge.

On the other hand, time scales for dynamic problems which involve inertial effects need to consider a different scaling law where the time in the prototype is scaled as N rather than N^2 as is the case for diffusion events. Furthermore, the time scale for creep is unity. This conflict needs further consideration, especially in tests involving different types of events, such as stability of embankment during a seismic event. Before the seismic event, the consolidation time scales are used but during the event, significant water flow may be prevented due to relatively low permeability and the dynamic time scaling law is applied.

In some cases, the particular problem that is being modelled needs to be considered where one aspect of soil behaviour may be more significant than others and has to be correctly modelled.

APPLICATIONS

1. RIVERBANKS SUBJECT TO TIDAL FLUCTUATIONS

Wong, et al., (8) designed and tested a river bank slope problem where continuous tide movement resulted in a cumulative deflection of piles. The tests were carried out at the NUS Geotechnical Centrifuge Laboratory (Figure 2). The model was set up in a container with a back panel which contained a water tank that could be moved up and down (Figure 3). The tank movement draw-downs or raises the water level in the model river bank, simulating tide movements. Model piles were installed with attached

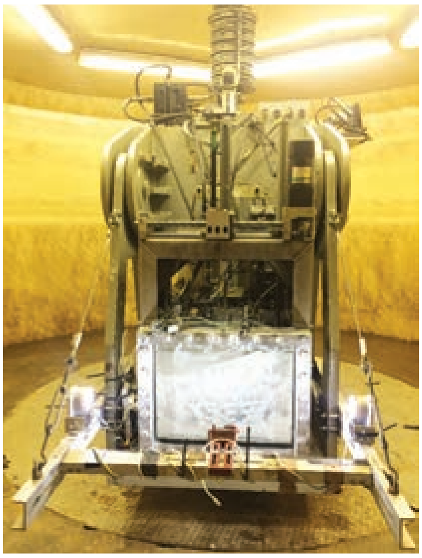

Figure 2: Riverbank slope model set up at NUS geotechnical centrifuge laboratory

Figure 3: Water tank fixed to back panel of container to simulate tidal fluctuation [8]

strain gauges while lasers were used to measure pile head deflection.

The maximum lateral soil movements (Figure 4) and bending moments occurred at the mid-slope locations and showed a decreasing trend over time while pile head movements were observed to increase over continuous cycles, reaching an asymptote (Figure 5).

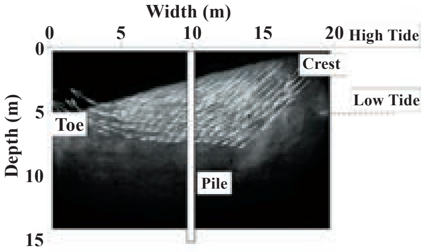

Figure 4: Soil movements captured using imaging and PIV techniques [8]

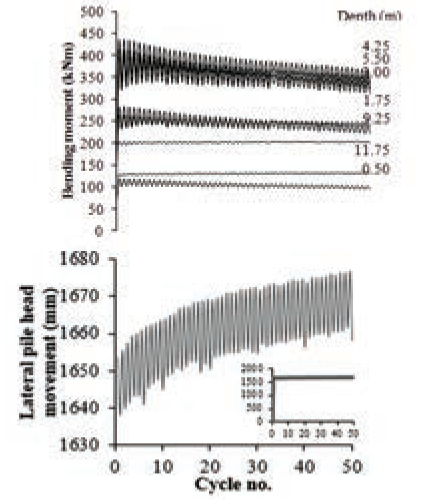

Figure 5: Development of pile bending moment and head movements over continuous cycles of fluctuations [8]

With each cycle of drawdown, the slope moved towards the river and during the subsequent water level rise, the slope rebounded from the river but did not completely recover. Thus, a cumulative movement is seen over 50 cycles of fluctuation. Using miniature PPT embedded in the slope, it was observed that negative pore water pressures accumulated at the mid-slope and toe levels, possibly due to this cyclic shearing of the soil slope. The increase in the effective stresses due to the development of excess pore water pressure would reduce the bending moments over time. On the other hand, the creeping behaviour of the slope over each cycle would drag the pile with the slope, thus showing a continuous increase in pile head movements.

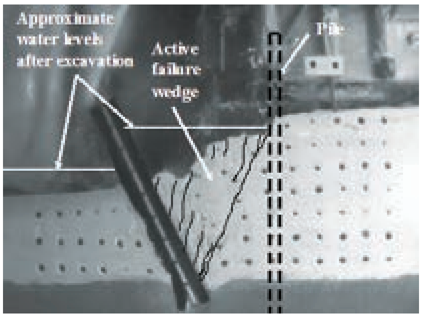

Figure 6: High resolution pictures showing failure mechanism of soil behind retaining wall [10]

These observations suggest that, in the short term, bending moments were more critical. Meanwhile, due to the continuing increase in pile head movement, an uncapped pile foundation system can be vulnerable when embedded in the riverbank and can face serviceability issues in the long-term.

2. DEEP EXCAVATIONS AND TUNNELS

Ong, et al., (9) and *Leung, et al., (10)* carried out a series of tests to determine the behaviour of piles behind a stable and failing retaining wall (see Figure 6), respectively. By controlling the amount of fluid in the latex bag, the excavation process could be sequentially modelled in-flight.

The test results showed that after excavation, the generated excess negative pore pressure would dissipate, resulting in a continuous increase in pile bending moment as well as pile head movements even after the excavation had ceased.

Tunnel construction is another area where centrifuge can be used to study the detrimental effects of induced vertical and lateral movements on the existing foundations of buildings above and near the affected areas. *Sharma, et al., (11)* used a relatively new approach to model tunnel construction in a centrifuge i.e. by using polystyrene foam which could be dissolved in-flight using acetone. Thus, proper construction sequence can be simulated. The tunnel lining was installed with strain gauges and the surface measurements carried out with LVDT for subsequent interpretation of soil-structure interaction.

3. SEISMICITY AND DAMS

Seismic events or earthquakes are modelled in the centrifuge by using shaking tables and shear boxes. A rare and interesting case is where dams are modelled for earthquake scenarios. In case of concrete dams, the energy required to fracture and for cracks to form, is dependent on grain size. Scaling down the size of aggregates used in concrete so as

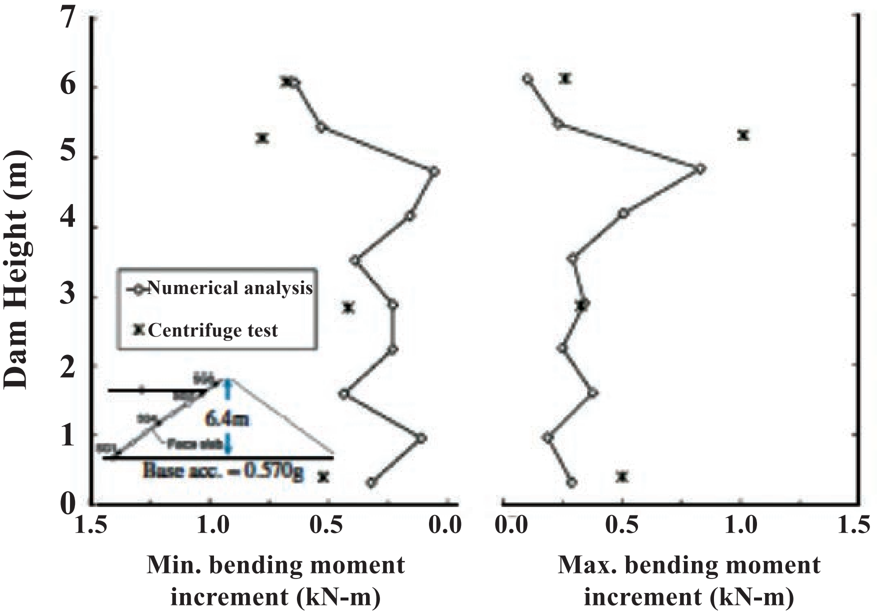

Figure 7: Comparison of centrifuge test and numerical analysis [12]

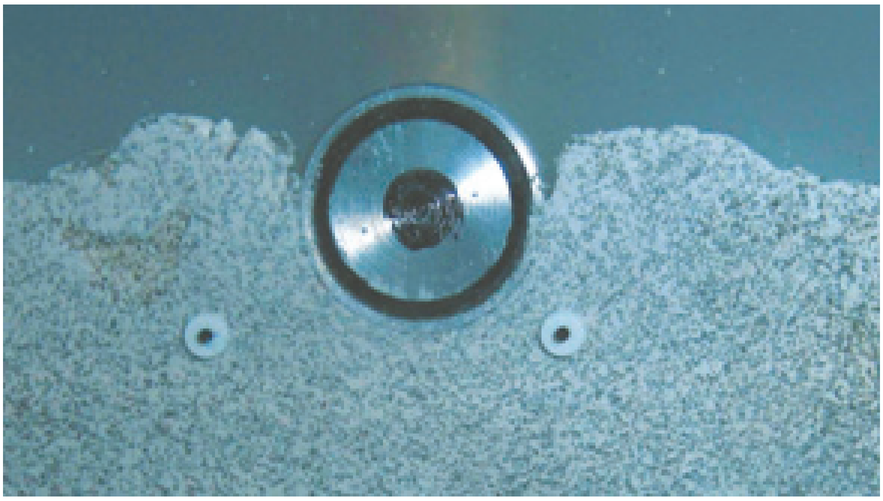

Figure 8: Model pipe on seabed as seen through a perspex window [13]

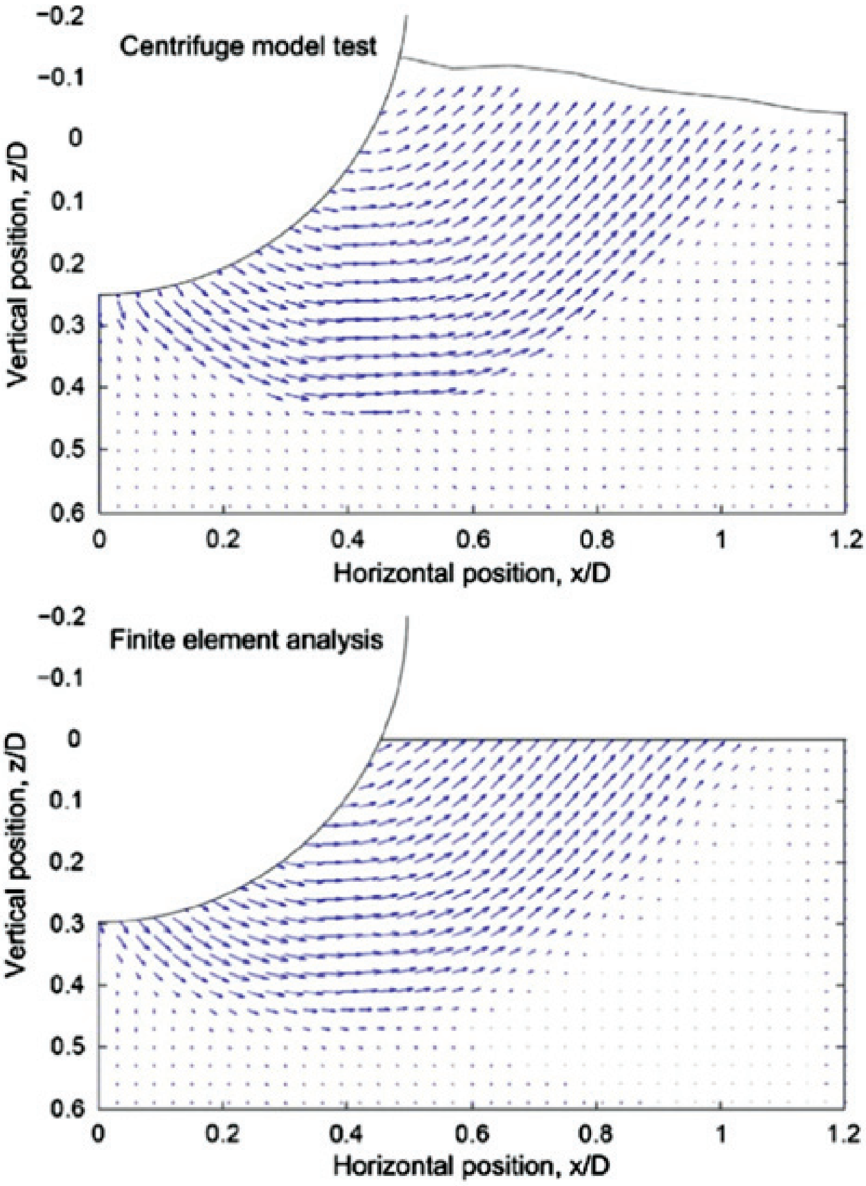

Figure 9: Comparison of soil vectors from centrifuge and numerical tests [14]

to achieve the same concrete as the prototype means that dam failure mechanism will be affected.

The scaling of energy and particle sizes will mean a special mix of concrete is required. Furthermore, in order to simulate the correct pore pressure response, high viscosity fluid has to be used to saturate the soil.

Kim, et al. (12) successfully carried out dynamic centrifuge tests on two major dam types: Earth-core rockfill dam and concrete-faced rockfill dam. They found that residual settlements and displacements were relatively small and failure mostly occurred by surface sliding. Furthermore, they verified their findings by carrying out numerical analyses. The results of the analysis closely resembled the results of centrifuge tests (Figure 7).

4. OFFSHORE INFRASTRUCTURE

Offshore infrastructure, as used in the oil and gas industry, is a unique situation where environmental loading plays an important role. A lot of research has been carried out in this area, including studies on offshore foundation systems, anchoring systems, submerged pipelines and submarine landslides.

A common application in this field is to model soil-pipe interactions on a sea bed. *Dingle, et al., (13)* carried out studies on the embedment and lateral breakout mechanism of pipes in soft clay. Using high-resolution pictures (Figure 8) to capture soil behaviour and load displacement data from the centrifuge tests, the brittle breakout mechanism was identified.

Furthermore, soil vectors generated from the images during centrifuge testing closely followed the results from numerical studies (Figure 9).

CONCLUSION

Centrifuge technology presents many advantages in terms of time, cost, repeatability (consistency) and quality of acquired data if the centrifuge model is diligently idealised, based on the established scaling laws and sound geotechnical engineering knowledge.

While designing for strength based on a given factor of safety is still common, performance-based design is becoming as important. With the increasing number of centrifuge facilities being constructed in Asia, coupled with more innovative test methods being applied in centrifuge modelling, this means that engineers now have the opportunity to perform forensic engineering and parametric study on challenging and complex real-life geotechnical problems, which would otherwise be too costly to test (e.g. fullscale test).

The ability to study and understand a potential failure mechanism is the basis for developing innovative engineering solutions. Therefore, centrifuge modelling can be readily used to verify complex soil-structure interaction problems and to complement numerical modelling, laboratory testing as well as field observational approach. ■

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Authors' Biodata

Ir. Assoc. Prof. Dr Dominic Ong Ek Leong, *obtained his Bachelor's Degree from the University of Western Australia (UWA) and his PhD in Geotechnical Engineering from the National University of Singapore (NUS). He is currently an Associate Professor and Director of the Research Centre for Sustainable Technologies, Faculty of Engineering, Computing & Science, Swinburne University of Technology Sarawak Campus and an EXCO Member of the Association of Consulting Engineers Malaysia (ACEM) Sarawak Branch, Vice-Chairman Institution of Engineers Malaysia (IEM) Sarawak Branch and a Founding Member of the Malaysian Geotechnical Society (MGS) and the Malaysian Society for Trenchless & Tunnelling Technology (MSTTT).*

He is also an Editorial Board Member of the UK's Institution of Civil Engineer (ICE) journal, Geotechnical Research and SEA Geotechnical Society's Geotechnical Engineering journal.

IEM DIARY OF EVENTS

Title: 2-Day Course on Executive Management In Primavera P6

24-25 January 2018

Organised by: Project Management Technical Division
Time : 9.00 a.m. - 5.30 p.m.
CPD/PDP : 14

Title: 2-Day Seminar on "Fire Control Concept & Design of Active Wet System"

24-25 January 2018

Organised by: Building Services Technical Division
Time : 8.30 a.m. - 5.15 p.m.
CPD/PDP : 13

Title: Talk on "Introduction to BIM for Civil and Structural Engineeers Series - Overview and the Malaysia Roadmap" (2nd Session)

25 January 2018

Organised by: Civil & Structural Engineering Technical Division
Time : 5.30 p.m. - 7.30 p.m.
CPD/PDP : 2

Title: 5-Day Course on PMP Exam Prep Combo

5-9 February 2018

Organised by: Seniors Special Interest Group & Project Management Technical Division
Time : 9.00 a.m. - 5.00 p.m.
CPD/PDP : Applying

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CONGRATULATIONS

*Congratulation to **Ir. Dr Ahmad Anuar bin Othman** on being promoted as **State Director, Jabatan Pengairan Dan Saliran Negeri Perak (JPS)** on **15 December 2017**.*