*Physical Modelling in Geotechnics*


# The 850 g-ton modular drum centrifuge facility at HKUST

L. Zhang, W. Lu, P.V. Laak & S. Baghbanrezvan
*Department of Civil and Environmental Engineering, The Hong Kong University of Science and Technology, Hong Kong, China*

**ABSTRACT:** To meet the needs of both teaching and research, an 850 g-ton, 250 g, 2.2 m diameter drum centrifuge has recently been established at the Hong Kong University of Science and Technology. The modular centrifuge is capable of spinning two test environments: the drum environment and the beam environment. A unique three-dimensional (3D) robot is attached to the tool table on the drum centrifuge to allow 3D movement and to apply loads at any position in the model in-flight. A model that is 0.7 m wide x 0.4 m deep x 6.91 m long within the drum's cylindrical channel simulates prototype geotechnical systems of up to 175m wide x 100 m deep x 1727 m long. Long-distance landslides and debris flows can be simulated. The drum centrifuge facility will perfectly complement the existing 400 g-ton beam centrifuge facility: the beam centrifuge is capable of simulating centralized problems (e.g. piles), while the drum centrifuge is capable of simulating distributed problems occurring over distances. The new drum centrifuge is installed next to the beam centrifuge, so that it can be operated and maintained by the existing experienced engineers and technicians.

**Keywords:** centrifuge testing, drum centrifuge, natural hazards, wave loading.

## 1 INTRODUCTION

The fundamental principle of centrifuge modelling is to recreate stress conditions, which would exist in a prototype, by increasing *n* times the “gravitational” acceleration in a 1/*n* scaled model in the centrifuge. This guarantees that the stress-strain behaviour of the model is the same as that of the prototype (Schofield 1980; Garnier et al. 2007). Hence, centrifuge models reproduce the prototype behaviour better than other types of physical modelling. Indeed, centrifuge modelling is a proven and powerful technique for revealing physical mechanisms, calibrating theoretical and numerical analysis, predicting the performance of complicated engineered systems, and evaluating design alternatives (Zhang and Wong 2007; Chu et al. 2021).

The Geotechnical Centrifuge Facility (GCF) at the Hong Kong University of Science and Technology houses a 400 g-ton, 8 m diameter beam centrifuge (Shen et al. 1998). Since its commission in 2001, the centrifuge has been used extensively in collaborative research activities. A wide range of complex geotechnical problems such as rain-induced landslides and vegetation -soil-atmosphere interactions have been simulated. The centrifuge has also been used to solve important engineering problems such as the design of soil nails in loose-fill slopes and the evaluation of ground-improvement schemes for the third runway of the Hong Kong International Airport. The GCF has developed several state-of-the-art devices for centrifuge modelling, including a four-axis robotic manipulator (Ng et al. 2002; Kong and Zhang 2006), a biaxial shaking table (Ng et al. 2004), an energy-harvesting chamber (Ng et al. 2022), and an environmental chamber (Archer 2019).

The present beam centrifuge can operate at up to a maximum centrifugal acceleration of 150 g with a payload of 2.7 tons, with the largest prototype dimensions of 188 m in plan and 128 m in height. Such dimensions are sufficient for many geotechnical problems such as slope stability and foundation modelling. However, a range of problems of great practical interest cannot be effectively modelled using the beam centrifuge because the boundary conditions imposed by the rigid walls of model containers are unrealistic. Examples of such problems include long-distance debris flows, wave loading, hillslope erosion, sediment transport, and contaminant transport (Phillips and Sekiguchi 1992; Gao and Randolph 2005).

To solve the pressing needs of both teaching and research and to enhance HKUST’s role as a centre for cutting-edge research into the physical modelling of geotechnical processes, an 850 g-ton, 250 g, 2.2 m diameter modular drum centrifuge has been recently developed. The new drum centrifuge facility perfectly complements the existing 400 g-ton beam centrifuge facility: the beam centrifuge is capable of simulating centralized problems (e.g. piles), while the drum centrifuge is capable of simulating distributed problems occurring over distances up to 1727 m long. The new drum centrifuge facility and the existing beam centrifuge facility together form a world-leading centrifuge cluster and provide a platform for researchers to expand their

*© 2022 KOREAN GEOTECHNICAL SOCIETY (KGS), Seoul, Korea, ISBN 978-89-952197-7-5*

scope in hazard prevention, offshore resource engineering, and environmental protection.

## 2 THE MODULAR DRUM CENTRIFUGE FACILITY AND ITS 3D ROBOT

The HKUST drum centrifuge is installed next to the existing beam centrifuge, so that it can be operated and maintained by the existing experienced engineers and technicians. The overall height of the machine is 4.1 m, and the height at which operator access is required for modelling operations is 1.97 m above the base of the machine. Shown in Figure 1, a 'mezzanine' floor was constructed to replace a portion of the main floor in the foundation pit, with a central opening of approximately 2.6 m diameter to provide clearance for the 2.5 m diameter centrifuge drum.

The modular drum centrifuge is a flexible modular centrifuge capable of spinning two test environments: a drum environment and a beam environment. In the drum environment, the centrifuge can produce a radial acceleration of up to 250 g on a test payload of 3480 kg, corresponding to a maximum speed of about 450 rotations per minute and a capacity of 850 g-ton. These figures make the HKUST drum centrifuge the largest of its kind in the world. The test drum channel is 2.2 m in diameter, 0.7 m in width and 6.91 m in length (175 m wide and 1727 m long at prototype scale at 250 g). As shown in Figure 2(a), two twin-concentric shafts, the main and inner shaft, are equipped. The main shaft is driven via a wedge belt transmission by a 45 kW, 4-pole, 3-phase electric induction motor. The inner shaft is driven using a separate induction motor (5.5 kW), which controls the speed of the tool table and actuator. The base platform is supplied with two independent Ethernet-based 32-channel data acquisition systems (DAS) for the drum channel and the tool table, respectively.

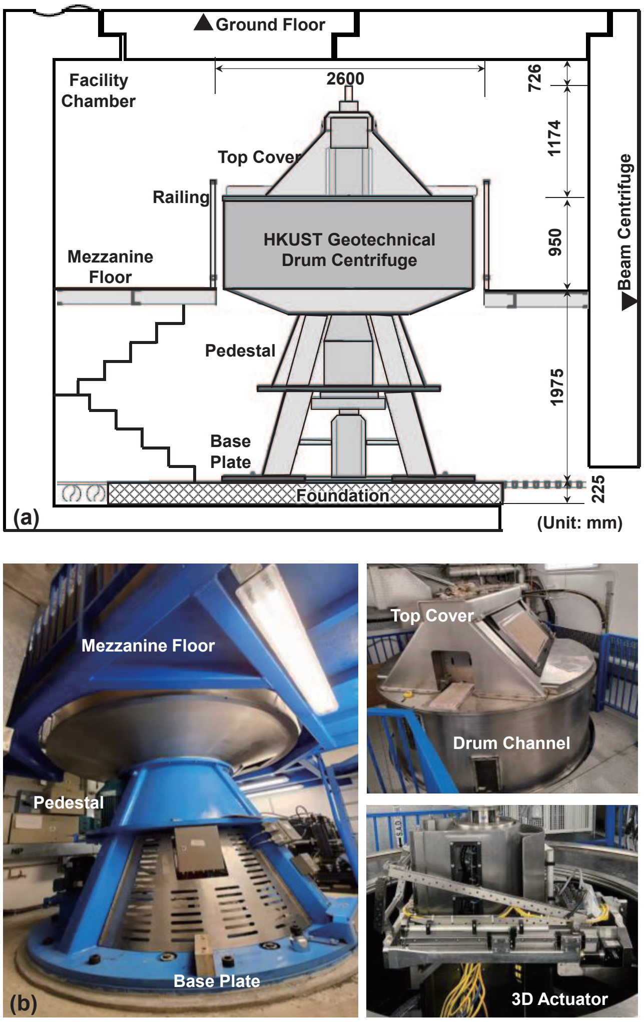


Fig. 1. Cross-section and chamber of the drum centrifuge facility.

Most geotechnical structures are subject to combined vertical (V), horizontal (H) and moment (M) loadings, and the bearing capacity envelope can be described by a 3D ellipsoid (e.g., Cassidy et al. 2002). Hence a multi-axis 3D loading actuator is developed for the drum centrifuge facility (Figures 1 and 2(b)). The actuator is attached to the top of the tool table, which is able to interact with the model in the drum channel by accurate positioning and load application in the X- (circumferential), Y- (vertical) and Z-(radial) directions. The X-axis motion is provided by a harmonic gearbox; The Y-axis motion is provided by a carriage constructed from high strength stainless steel that runs up and down the column on a pair of linear bearing rails with recirculating ball shoes; The Z-axis motion is provided by aluminium alloy arms running on linear bearing rails along both sides of the carriage connecting to a 'T' shaped aluminium alloy faceplate, which can be attached with instruments that interact with the model in the drum channel. The load actuator is designed to move at velocities of 0-5 mm/s, with a load capacity of ±5 kN.

*© 2022 KOREAN GEOTECHNICAL SOCIETY (KGS), Seoul, Korea, ISBN 978-89-952197-7-5*

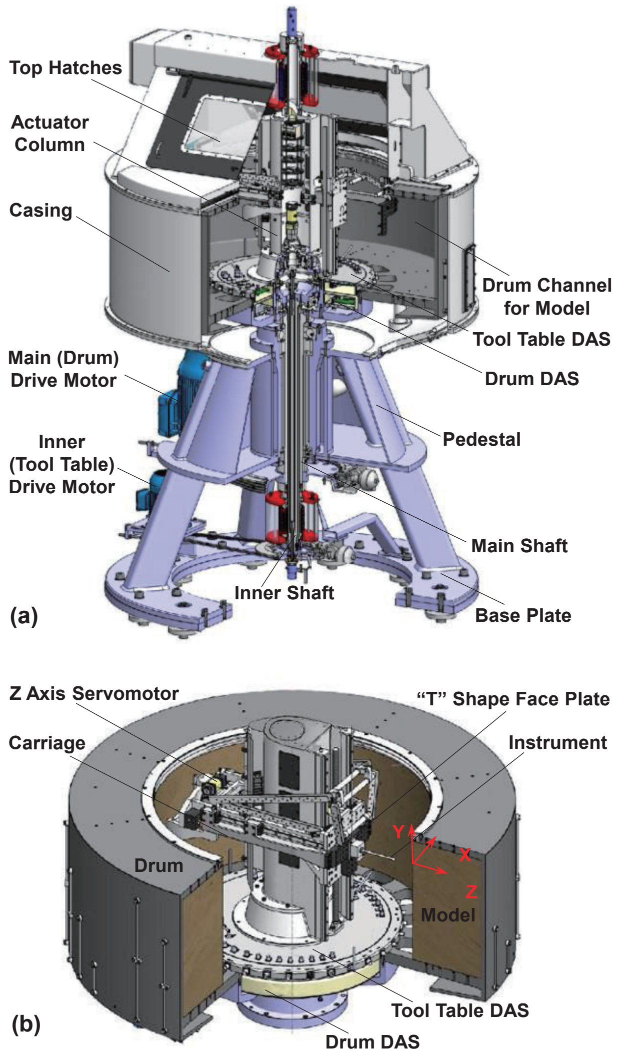


Fig. 2. The HKUST drum centrifuge and 3D loading actuator.

The versatile 3D capability of the unique loading actuator enables it to form the basis of various in-flight model formation tools:

(1) Sand rainer: A downward feed pipe is attached to the "T" shape faceplate to allow sand fall from a certain height into the drum channel in-flight and achieve a designated density. An assistant levelling mechanism is designed to make a uniform distribution of sand in the Y-direction.

(2) Soil pourer: This is similar to the sand rainer, but with a different feed pipe for different flow characteristics.

(3) Model profiler: The actuator can achieve the motions required for profiling the surface of the model.

A selected set of basic geotechnical testing systems are included in the facility, including model preparation accessories (i.e. in-flight feed pipes, a clay mixer, a vacuum mixer and a consolidometer), miniature in-situ testing devices (i.e. a miniature cone penetrometer and a shear vane), a particle image velocimetry (PIV) system including cameras and software, and an instrumentation set for the purpose of testing and validating the new facility. Sample preparation in a drum centrifuge can be more difficult than in a beam centrifuge (Springman et al. 2001; Laue et al. 2002; Gao and Randolph 2005). The unique sample preparation accessories for this facility help solve this problem.

## 3 MODEL PACKAGE FOR SIMULATING - LONG-DISTANCE LANDSLIDES, DEBRIS FLOWS, AND HILLSLOPE EROSION

In order to simulate long-distance landslides, debris flows, or hillslope erosion, a material storage tank with a moveable endplate has been designed. Materials, such as landslide or debris mass and water can be stored in the tank, and released in-flight at a designated height. When simulating the initiation of rainfall-induced landslides, rain nozzles will be implemented to the fixed plate.

The test package for simulating long-distance geohazards can be divided into two processes: bed model preparation and top material releasing. After the drum centrifuge spins to the required speed, the bed model material is fed into the drum channel. Afterwards, the 3D actuator is employed to profile the surface of the model, such as a hillslope, a landslide dam, or a coastal embankment. Subsequently, the endplate of the material storage tank or the rain spray nozzles will be opened via a remotely-controlled hydraulic valve. The landslide mass will be released from the design height, slide over the bed model, and run for a long distance. Two twin test packages can be placed to ensure a good balance.

Two instrumentation systems will be used to capture the sliding process and bed erosion: (1) a compact high-speed image capture system using a high-speed camera and PIV techniques, and (2) an array of photoconductive sensors and Doppler velocimeters to capture the distribution of flow velocity along the long drum channel. The high-speed camera will allow the dynamic failure process and the fluid-soil bed interface behaviour to be captured. The PIV is a versatile tool for measuring the displacement, velocity and strain fields.

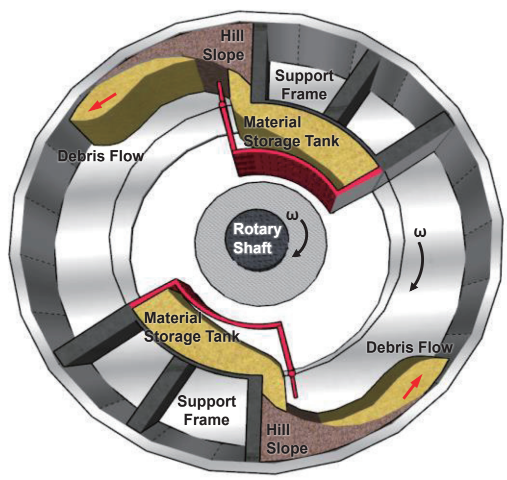


Fig. 3. The test package of long-distance debris flow.

*© 2022 KOREAN GEOTECHNICAL SOCIETY (KGS), Seoul, Korea, ISBN 978-89-952197-7-5*

## 4 ONBOARD WAVE GENERATOR

A wave generator (Fig. 4) is being developed for the drum centrifuge to facilitate the study of coastal scouring, wave-induced liquefaction of the seabed, and resilience of offshore structures such as breakwaters, levees, wind turbines, port and harbour construction, and bridges against complicated wave and tsunami loadings. The wave generator is driven by a hydraulic system and able to generate two types of waves: (a) shallow water coastal waves generated using a piston wave generation mechanism, and (b) deep ocean waves generated using a flap wave generation mechanism.

The system incorporates a wave generator utilizing a closed-loop, displacement-controlled hydraulic servo-actuator to displace a movable plate to produce water waves in the wave tank. A custom computer program will be coded to permit the generation of a wide variety of waveforms. The wave tank is designed to be installed within the drum channel and is configured as a three-layer stack of functional sub-assemblies: the hydraulic power unit layer, the model instrumentation layer, and the wave tank layer. The hydraulic power unit layer is a general-purpose 200 bar hydraulic power supply that can be used with a wide range of ancillary hydraulic instrumentation. The other layers are specific to this wave tank system.

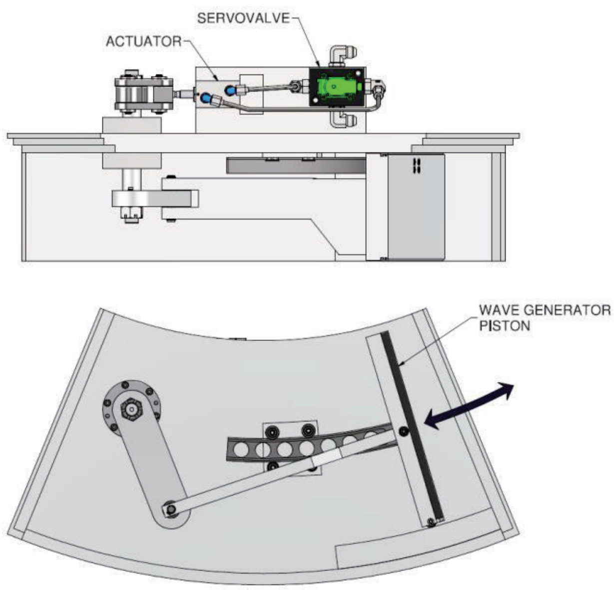


Fig. 4. Wave generator segment.

## 5 SUMMARY

This paper introduces key features of the new 850 g-ton, 250 g geotechnical drum centrifuge at the Hong Kong University of Science and Technology, which is capable of simulating distributed problems occurring over distances up to 1727 m long. The centrifuge, as well as its multi-axis 3D loading actuator, miniature wave generator, and test packages, make it a powerful tool for research into mountain and estuary hazard mitigation, ocean engineering, and environmental protection.

## ACKNOWLEDGEMENTS

The drum centrifuge facility is funded by the Research Grants Council of the Hong Kong SAR (Grant No. C6021-17E) and the Hong Kong University of Science and Technology.

## REFERENCES

Archer, A. 2019. *Climate change impact on unsaturated embankments considering temperature and humidity: centrifuge modelling.* PhD thesis, Hong Kong: The Hong Kong University of Science and Technology.

Cassidy, M.J., Byrne, B.W. & Houlsby, G.T. 2002. Modelling the behaviour of circular footings under combined loading on loose carbonate sand. *Geotechnique* 52(10): 705 -712.

Chu, L.M., Lu W.J. & Zhang L.M. 2021. Centrifuge modeling of vessel impact on bridge fender systems. *J. Geotech. Geoenviron. Eng.* 147(5): 04021015.

Gao, F.P. & Randolph, M.F. 2005. Progressive ocean wave modelling in drum centrifuge. Frontiers in offshore Geotechnics ISFOG 2005, London, Taylor & Francis Group.

Garnier, J., Gaudin, C., Springman, S.M., Culligan, P.J., Goodings, D., Konig, D., Kutter, B., Phillips, R., Randolph, M.F. & Thorel, L. 2007. Catalogue of scaling laws and similitude questions in geotechnical centrifuge modelling. *Int. Journal of Physical Modelling in Geotechnics* 3: 1-23.

Kong, L.G. & Zhang, L.M. 2006. Rate-controlled lateral-load pile tests using a robotic manipulator in centrifuge. *Geotechnical Testing Journal* 30(3), DOI:10.1520/GTJ13138.

Laue, J., Nater, P., Springman, S.M. & Gramiger, E. 2002. Preparation of soil samples in drum centrifuges. *Physical Modelling in Geotechnics: ICPMG'02*, Phillips, Guo & Popescu (eds). London: Taylor & Francis Group, 143-148.

Ng, C.W.W., Van Laak, P.A., Zhang, L.M., Tang, W.H., Zong, G.H., Wang, Z.L., Xu, G.M. & Liu, S.H. 2002. Development of a four-axis robotic manipulator for centrifuge modelling at HKUST. *Proc. Int. Conf. on Physical Modelling in Geotechnics*, St. John's Newfoundland, Canada, 71-76.

Ng, C.W.W., Li, X.S. Van Laak, P.A. & Hou, Y.J. 2004. Centrifuge modelling of loose fill embankment subjected to uni-axial and bi-axial earthquakes. *Soil Dynamics and Earthquakes Engineering* 24(4): 305-318.

Ng, C. W. W., Baghbanrezvan, S., Lau, S. Y., Sanchez, M., & Zhou, C. 2022. Effects of Hydrate Dissociation on Vertical Casing–Sediment Interaction in Carbon Dioxide Hydrate–Bearing Sand: Novel In-Flight Centrifuge Modeling. *J. Geotech. Geoenviron. Eng.* 148(3): 04021199.

Phillips, R. & Sekiguchi, H. 1992. Generation of water wave trains in drum centrifuge. *Proc. Technology Ocean'92*, Yokohama, Japan, 1, 29-34.

Schofield, A.N. 1980. Cambridge geotechnical centrifuge operations. *Geotechnique* 30: 227-268.

Shen, C.K., Li, X.S., Ng, C.W.W., Van Laak, P.A., Kutter, B.L., Cappel, K. & Tauscher, R.C. 1998. Development of a

Springman, S.M., Laue, J., Boyle, R., White, J. & Zweidler, A. 2001. The ETH Zurich geotechnical drum centrifuge. *Int. Journal of Physical Modelling in Geotechnics* 1, 59-70.

Zhang, L.M. & Wong. Eric Y.W. 2007. Centrifuge modelling of large diameter bored pile groups with defects. *J. Geotech. Geoenviron. Eng.* 133(9): 1091-1101.