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Physical Modelling in Geotechnics

Development of NUS's Mark II geotechnical beam centrifuge

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ABSTRACT: After more than 3 decades of centrifuge modelling using the existing 4m diameter 40 g-ton beam centrifuge, NUS has committed to rejuvenating its geotechnical centrifuge laboratory with a Mark II. The motivation of a new beam centrifuge stems largely from the increasing complexity in geotechnical problems due to urban development where infrastructures are constructed at close proximity. As such, more details of the model have to be acquired in order to have a better appreciation of the geotechnical issue. This led to the development of the 9m diameter 150 g-ton Mark II beam centrifuge with larger platform size and payload capacity to provide greater flexibility in modelling. The payload plan dimension and headroom are 1 sqm and 1.5m respectively, which is considered a massive upgrade from the current 40 g-ton Mark I centrifuge. This paper briefly introduces the development and considerations of the Mark II centrifuge facilities.

Keywords: centrifuge, Mark II, specifications, design consideration

1 INTRODUCTION

The year of 2022 marks 32 years of centrifuge modelling at the Department of Civil and Environmental Engineering (CEE) in the National University of Singapore (NUS). Designed by Professor Lee Fook Hou who built the laboratory from scratch with guidance from Professors A.N. Schofield of the University of Cambridge, R.F. Scott of the California Institute of Technology and T. Kimura of Tokyo Institute of Technology, along with the help of a local steel fabricator making pressure tanks (Lee et al. 1991), a total of more than 90 postgraduate students have graduated with the use of the beam centrifuge since the year 1980.

The motivation of the development of the Mark I beam centrifuge stems from the mission and background of the geotechnical engineering group at NUS CEE. The mission of the group is to provide technical leadership to advance geotechnical engineering research, education and practice for sustainable and responsible development. It also seeks to develop transformational technologies for large-scale space creation and generation in a land-scarce Singapore. As a leading university in a developing nation back then, the group felt obliged and an inclination to serve Singapore's needs in urban development, particularly in major civil engineering activities such as land reclamation, ground improvement, deep excavation, tunnelling, underground construction, foundation, slope stabilisation, geosynthetics, protective technology, offshore geotechnics, geohazards and risk management, relevant to Singapore's local geological landscape. Along the way, the group was lacking of a reliable means to assess certain geotechnical challenges. Often these problems were studied by means of numerical analysis, supplemented by some field instrumentation trials. However, such information was often insufficient. In order to properly calibrate numerical analyses, it is necessary to have model tests which obeys the correct scaling consideration. This incentivised NUS to develop a centrifuge testing facility. Another advantage of centrifuge modelling is its lower cost as compared to field instrumentation.

Being the only centrifuge laboratory in Southeast Asia, the department has been actively collaborating with the industry to study unique and challenging geotechnical issues they faced till to date. At this moment, the Mark I beam centrifuge is still operational and efficient in running multiple tests a week due to its compact design. However, with urban development becoming more complex with closer proximity between infrastructure, a global appreciation of geotechnical phenomenon is no longer sufficient. Instead, more details of potential failure mechanism and deformation profile are necessary in such geotechnical models. This motivated the University to invest in a larger beam centrifuge (the Mark II) with larger test platform size and payload capacity to offer greater flexibility in modelling to support such research pursues.

2 THE MARK II BEAM CENTRIFUGE

Fig. 1 shows the impression of the new Mark II beam centrifuge that has been constructed and awaiting delivery to NUS after the infrastructure is ready in mid-April 2022. An international tender was called in year 2016 and the successful tenderer of the Mark II centrifuge was Beijing Star, which made most of the centrifuges in China. Offering the flexibility to customise key features of the centrifuge such as greater headroom and test platform plan area with a relatively smaller radius and lower power consumption at a competitive cost, the design of the centrifuge fitted well into the requirements of the research ambitions of the faculty members of NUS CEE.

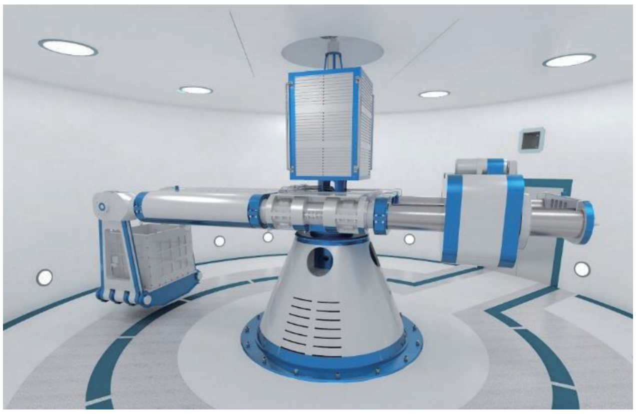

Fig. 1. Impression of NUS's Mark II beam centrifuge.

A high headroom is imperative to enable taller soil models fitted with overhanging equipment and instrumentations such as a sand rainer, lightings and camera to be tested. The high headroom also enables pore water and earth pressure transducers to be easily checked for accuracy as well as allowing in-flight consolidation of thick soft clays to be carried out.

A test platform plan area is ideal to enable considerably large soil models to be tested without excessively scaling down the prototype. This would allow greater details of soil-structure interaction to be captured as well as more room for placement of instrumentation at key locations in the soil model.

In view of the tight land space available for the beam centrifuge laboratory, a relatively shorter radius of the centrifuge no longer than 4.5m for the desired test platform size of 1 m^2 and 1.5m headroom was necessary. This limited several off-the-shelves beam centrifuge models offered by well-established centrifuge manufacturers.

Finally, low power consumption of the centrifuge no greater than 220kW during operation was desired due to limited electrical power supply along the services corridor next to the proposed laboratory. The cost of laying fresh high tension electrical cables would simply be uneconomical to support this single facility which otherwise would be better invested in the centrifuge.

The maximum acceleration and payload capacity are 120g and 150g-ton respectively. The group felt that the acceleration beyond 120g is not essential since models are not expected to be scaled excessively so as to acquire greater detail of potential failure mechanism and deformation in alignment with the motivation of developing the larger centrifuge.

The outcome of centrifuge tests is as good as the quality and comprehensiveness of the information acquired from instrumentation. Table 1 shows the detailed specifications of the associated features of the centrifuge. Ample voltage, current and strain channels have been catered for the data acquisition system. A total of 8 cameras have also been provided to offer visual of the testing and for safety. Emergency stop buttons as well as a safety ledge switch have also been incorporated in the design for staff working in the chamber and control room. Power consumption was kept no higher than 220 kW at maximum acceleration and payload due to power supply limitation. The centrifuge also comes with a fibre optic system, 4 ports of hydraulic oil, 2 ports of water and 1 port of air supply to facilitate on-board equipment. The in-flight automatic balancing capability has been included so as to minimize the effort and time to move the counterweights as well as to cater for loss of mass during spinning.

Table 1. Features of the centrifuge.

Description	Specifications
Data Acquisition System	64 channels (16 voltage channels, 16 current channels and 32 strain channels). LAN Speed 1 Gbits/s
Visual Surveillance System	8 cameras (centrifuge enclosure, model package and control room)
Power Consumption	Within 220kW at max. acc. and payload
Power Slip Rings	30A, 410V_{RMS}, 8 lines
Signal Slip Rings	1A, 220V DC 60 nos.
Fibre Optic Rotary Joint	4 passages, 1 GHz transmission rate
Hydraulic Oil	4 passages, 21MPa working pressure, 10-50˚ temp.
Water	2 passages, 1.5MPa working pressure, 10-50˚ temp
Air	1 passage, 0.8MPa working pressure
In-flight Automatic Balancing	Range 50+/-1kN, within 2 mins.

3 RESEARCH PLANS WITH THE MARK II CENTRIFUGE

The aspiration of NUS CEE is aligned with sustainability in construction. In geotechnical engineering, research is directed towards 4 tracks, namely, 1) utilization of underground space, where details of congested infrastructures in the model may be studied in greater detail on the larger platform of the Mark II centrifuge, 2) reuse, recycle and alternative green materials, involving the study of recycled and green materials in construction such as the incineration bottom ash (IBA) for land reclamation fill, 3) foundation rehabilitation and reuse, which investigates foundation reuse and retrofitting as an alternative to removing existing deep foundation, and 4) sustainable ground improvement, that considers solutions such as controlled modulus columns to ascertain its performance as compared to traditional piles. These tracks are in alignment with the government's Research Innovation and Enterprise 2025 (RIE2025) plan's in the category of Urban Solutions and Sustainability (USS), with the objective of further strengthening the nation's capabilities in building Singapore as a liveable, resilient, sustainable and economically vibrant city (NRF, 2021). In addition to geotechnical engineering research, the centrifuge would also be open to other disciplines of civil engineering and wider engineering community, such as the study of progressive collapse, sediment transport and contaminant diffusion, as well as high impact equipment testing.

Moving forward, NUS CEE hopes that the rejuvenation of its centrifuge laboratory would continue to meet its mission of advancing geotechnical engineering to support a more sustainable urban construction culture, along with its contribution to national development in space creation.

4 CONCLUSIONS

The investment in developing a new large beam centrifuge is a strong indication of NUS's commitment to physical modelling in geotechnics as well as the role of physical modelling in addressing emerging urban sustainability challenges such as utilisation of underground space amid the congestion in subterranean construction activities, recycled and alternative materials in construction, foundation rehabilitation and reuse, and sustainable ground improvement solutions. The Mark II beam centrifuge specifications have been catered to be compatible to these challenges with emphasis on platform size, headroom, as well as ample data acquisition channels supported with hydraulic oil, water and air supply to facilitate a multitude of test setups. An in-flight automatic balancing feature has also been considered for ease of testing and safety.

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