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Advancing Australia's facilities for physical modelling in geotechnics

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Abstract
This paper presents details of the advancements of the Australian Research Council Centre of Excellence for Geotechnical Science and Engineering to the apparatus, facilities and methods for physical modelling in geotechnics. This advancement includes (i) the launch of a National Geotechnical Centrifuge Facility with a new 10 m diameter fixed beam centrifuge that will be capable of spinning 2.4 tonnes of soil at 100 gravities, (ii) a new mobile soft soil in situ testing laboratory, (iii) a new national facility for the cyclic testing of high-speed rail and (iv) three recirculating flumes, called O-tubes, which are presented in another paper of this special issue. This paper provides an overview of this new equipment and the aims of the research that it will underpin. The equipment will provide enhanced possibilities for Australia to conduct project specific testing for future energy and transportation infrastructure developments, nationally and internationally.

ADVANCING AUSTRALIA'S FACILITIES FOR PHYSICAL MODELLING IN GEOTECHNICS

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ABSTRACT

This paper presents details of the advancements of the Australian Research Council Centre of Excellence for Geotechnical Science and Engineering to the apparatus, facilities and methods for physical modelling in geotechnics. This advancement includes (i) the launch of a National Geotechnical Centrifuge Facility with a new 10 m diameter fixed beam centrifuge that will be capable of spinning 2.4 tonnes of soil at 100 gravities, (ii) a new mobile soft soil *in situ* testing laboratory, (iii) a new national facility for the cyclic testing of high-speed rail and (iv) three recirculating flumes, called O-tubes, which are presented in another paper of this special issue. This paper provides an overview of this new equipment and the aims of the research that it will underpin. The equipment will provide enhanced possibilities for Australia to conduct project specific testing for future energy and transportation infrastructure developments, nationally and internationally.

1 INTRODUCTION

Due to the complex behaviour of soils and the development of new types of characterisation tools and foundation systems, there remain many geotechnical engineering problems that necessitate the validation and calibration of models and design methods using physical observations. Under the leadership of the Australian Research Council (ARC) Centre of Excellence for Geotechnical Science and Engineering (CGSE), the geotechnical community in Australia has collaborated to establish state-of-the-art testing facilities to model new geotechnical infrastructure associated with the energy and transport industries. Three major developments have been facilitated by the ARC through its Linkage Infrastructure Equipment and Facilities grant program: (i) a new 10 m diameter 240 g-tonne fixed-arm beam centrifuge, (ii) a new mobile soft soil *in situ* testing laboratory and (iii) a new prototype-scale, fully instrumented rail track for the cyclic testing of high-speed rail. These components will be key testing equipment for new national centres that incorporate 11 other Australian Universities, including the National Geotechnical Centrifuge Facility to be based at the University of Western Australia (UWA), the National Soft-Soil Field Station at Ballina in Northern New South Wales (and managed by the University of Newcastle (UoN), see Kelly *et al.*, 2014 and Li *et al.*, 2014) and a national facility for the cyclic testing of high-speed rail at the University of Wollongong (UoW). This paper provides an overview of this new equipment, the aims of the research that it will underpin and testing possibilities that it provides for Australian geotechnical engineers and industry.

2 NATIONAL GEOTECHNICAL CENTRIFUGE CENTRE

2.1 EXISTING FACILITIES

The CGSE at the UWA already operates a 3.6 m diameter 40 g-tonne fixed beam geotechnical centrifuge that is capable of accelerating experimental packages of 200 kg up to 200 g (Randolph *et al.*, 1991) and a 1.2 m drum centrifuge that can operate at up to 400 g (Stewart *et al.*, 1998) (Figure 1). These facilities have been an essential component of the development of new design and analysis methods for offshore foundations for over two decades. The strength and stiffness of geomaterials depend on the effective stress level, so only by spinning the soil and foundation models at high gravities can similitude between small scale models and full scale conditions be maintained. The sheer size of offshore engineering structures removes any potential for full scale physical tests; therefore, geotechnical centrifuge testing is essential.

The beam and drum facilities were established in 1989 and 1999, respectively, and have been in rapidly increasing demand from academia and industry, both national and international. The cumulative usage over the last three years is an average of over 500 days a year, making these geotechnical centrifuge facilities the most productive in the world. An average of 30 research projects are undertaken each year, enabling academics and PhD students to develop solutions for a broad range of offshore and onshore geotechnical issues. During the past 3 years, approximately 40% of this usage has been dedicated to research collaboration with industry. This percentage is double that of 2003, reflecting the wide and increasing recognition of benefits to industry brought by centrifuge modelling and serving as testimony to the

expertise developed at UWA. A key example of the increasing utilisation of centrifuge modelling by industry is the research projects undertaken within the ARC CGSE to support pipeline design for every major offshore pipeline that is currently in progress offshore of Australia, including the Browse, Gorgon, Ichthys, Pluto and Wheatstone projects.

The centrifuge facilities are supported by a team of eight electronic, mechanical and software engineers who have built, over the years, unmatched expertise in developing state-of-the-art modelling techniques. Models, instrumentation, image acquisition, motion control and data acquisition systems are designed and manufactured in-house, in direct collaboration with researchers and industry partners. These devices notably include an independent, self-powered wireless data acquisition system capable of sampling, filtering and converting data at 1 MHz and 16-bit resolution (Gaudin *et al.*, 2009) and a motion control system capable of applying complex loading or displacement sequences, including varying control modes on different axes, mimicking realistic typical offshore loadings and permitting the study of soil-structure interaction behaviour (De Catania *et al.*, 2010). These systems have been instrumental in enabling new research areas to be investigated within the CGSE.

The CGSE also maintains a library of marine soils from many oil and gas basins, including carbonate sand and silt from the North West Shelf and soft clay from West Africa. These natural soils are often utilised in our centrifuge testing programs to ensure that the outcomes and design methods are readily applicable to offshore conditions.

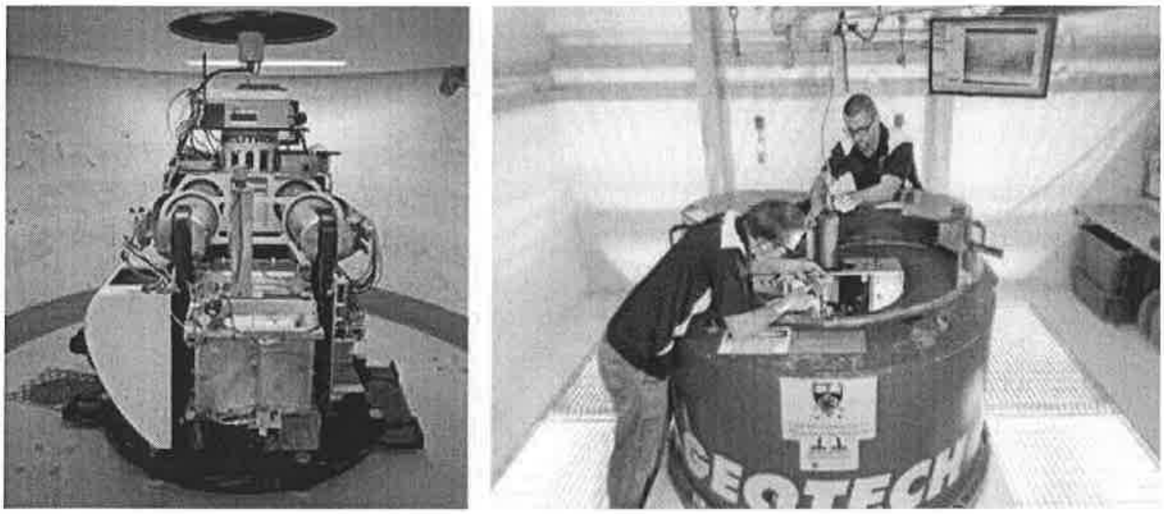

Figure 1: Existing centrifuge facilities at UWA: 3.6 m diameter 40-g tonne fixed beam centrifuge (left) and 1.2 m diameter 400 g capable drum centrifuge (right).

2.2 THE NATIONAL GEOTECHNICAL CENTRIFUGE FACILITY

The geotechnical community in Australia has collaborated to establish a new National Geotechnical Centrifuge Facility (NGCF) based at UWA. The two existing beam and drum centrifuges (Figure 1) will be augmented by a new Actidyn C72-2 240 g-tonne beam centrifuge that is 10 m in diameter (Figure 2). This centrifuge will spin a model package of 2,400 kg at 134 revolutions per minute, accelerating the soil to 100 g (or 1,400 kg at 130 g). This equipment, which represents the latest generation of geotechnical centrifuges, is equipped with automatic balancing, state-of-the-art robotic actuators, remote control and telepresence capabilities.

This new NGCF will provide additional capabilities related to robotic motion control, sensing, imaging and telepresence (to allow the close involvement of remotely located researchers and industry partners). These technologies will extend the current modelling capabilities to provide additional realism and will extend the measurement systems to allow the collection of more sophisticated and detailed records of events and deliver them to a wider user network. The size and technology associated with existing centrifuges restrict some of these developments and associated research.

The larger centrifuge and its state-of-the-art robotic control system and high-speed optic fibre communication system will enable the following:

1. New simulation techniques made possible by advanced robotics and a larger centrifuge platform:
   - Realistic simulation of modern 'in-flight' construction technologies with robotics, for example, staged embankment construction, with associated ground improvement techniques, such as soil nailing and the use of geotextiles;

- Realistic simulation of offshore design loadings encompassing whole-life behaviour applied to intricate model structures, such as multi-footing offshore platforms, pipelines and risers;
- Realistic scale modelling of deep excavation and tailing pond construction, accurately representing geostatic stresses and consolidation/swelling processes.

2. Next-generation centrifuge modelling technology made possible by a larger centrifuge platform and high speed optic fibre communications:
    - Precise sensing of 2D and 3D surface displacements using multi-camera photogrammetry;
    - Comprehensive wireless sensing of pressure, acceleration and displacement with micro-electro mechanical system (MEMS) technology;
    - Remote telepresence of collaborators using synchronous image and data transmission;
    - More detailed and instrumented models monitored with minimally intrusive sensor networks.

The new centrifuge will be housed in a purpose-built centrifuge laboratory 593 m^2 in size. The two existing centrifuges will also be relocated to the new laboratory, creating a unique hub of three centrifuges supported by an electronic laboratory, a mechanical workshop and a technical team of four operators, two electronic engineers, two software engineers and one mechanical engineer (Figure. 3). The soil preparation room, 191 m^2 in size, will serve the three centrifuges and will host three 1-g modelling stations that will benefit from the data acquisition and motion control systems developed for the centrifuges.

The development of hybrid numerical–physical testing, a novel scaled riser and pipeline sections, a four degree-of-freedom actuator and sophisticated load control algorithms will also be key projects for this new facility.

The NGCF has received the support of 6 Australian universities, the UWA, the UoN, the UoW, the University of Queensland, Monash University and the University of Adelaide, and forms an integral part of the ARC Centre of Excellence for Geotechnical Science and Engineering. The facility will underpin many research areas within the CoE but will also seek to service the entire Australian geotechnical community, both offshore and onshore, and reaffirm Australia's position as one of the foremost nations for geotechnical physical modelling.

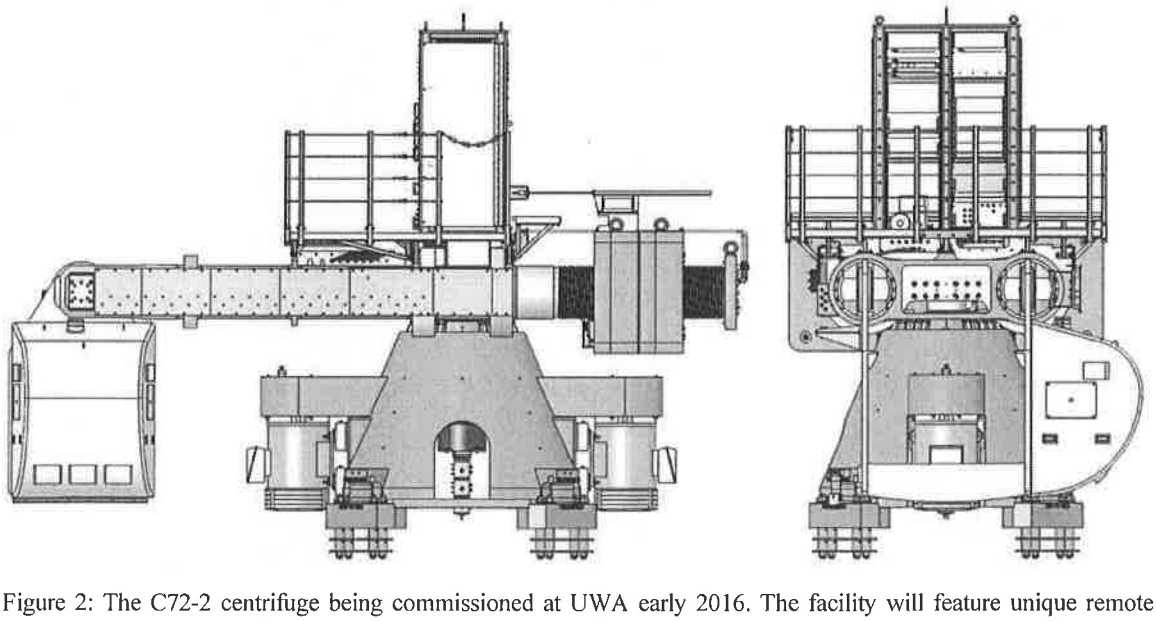

Figure 2: The C72-2 centrifuge being commissioned at UWA early 2016. The facility will feature unique remote control capabilities enabling continuous spinning over nights and weekends, as well as telepresence capabilities, enabling remote engagement with national and international collaborators.

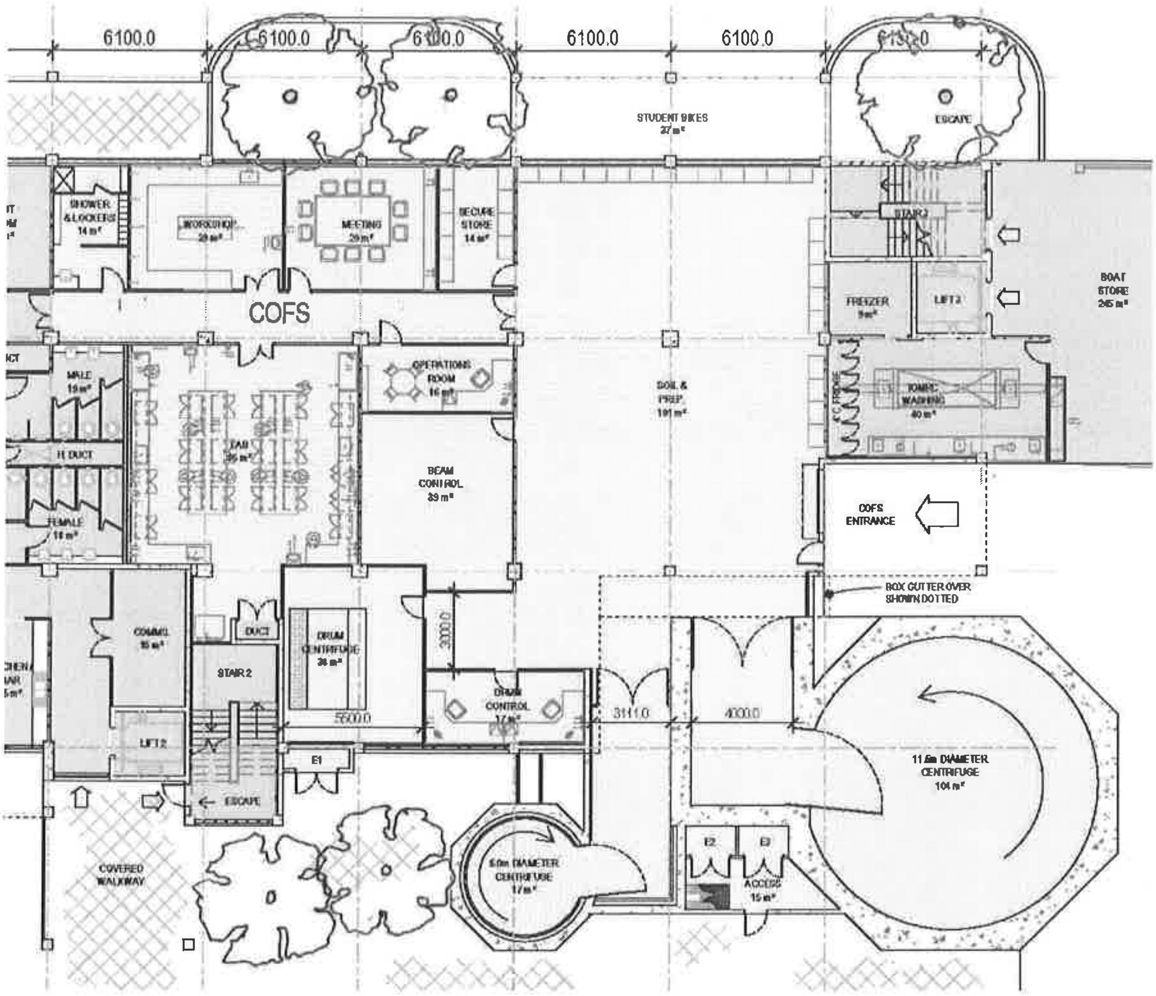

Figure 3: An overview of the new centrifuge laboratory layout showing the three geotechnical centrifuges, the soil preparation and 1g testing area, the control command rooms, the electronic laboratory and the mechanical support laboratory. This will be one of the largest geotechnical centrifuge laboratories in the world and the only one featuring three operating centrifuges.

3 MOBILE SOFT SOIL *IN SITU* TESTING LABORATORY

3.1 EXISTING *IN SITU* TESTING FACILITY

The CGSE through the UoN has operated the truck-mounted *in situ* testing facility "NewSyd" for the past 15 years (Figure 4). The current facility comprises a 200 kN truck-mounted testing rig that is operated on a full-time basis by two dedicated technical staff. The existing facility performs research testing to provide data for the development of *in situ* testing tools, interpretation methods and the general measurement of *in situ* soil properties. In addition, the facility is used to actively promote the use of advanced *in situ* testing by providing training for undergraduate and postgraduate students as well as professional engineers. Within the current operational model, the facility also undertakes a limited amount of commercial testing to cover ongoing operation and development costs.

A disadvantage of the current testing facility is that *in situ* tests must be conducted from the truck-mounted facility, which weighs 20 tonnes and is problematic for sites that are difficult to access, such as soft ground. Soft soils are no longer avoidable in major infrastructure projects. For example, the upgrade of the Pacific Highway along the east coast of Australia involves substantial lengths of raised embankment over extensive areas of soft clay. The *in situ* testing of these soils is particularly important because of the great difficulty of high quality soft soil sampling.

Figure 4: Current NewSyd facility at the Ballina site. Note the temporary working platform to support the vehicle weight.

3.2 THE NATIONAL MOBILE FACILIY FOR THE TESTING OF SOFT SOILS

A new crawler-mounted *in situ* soil testing laboratory capable of accessing soft and swampy sites is currently being commissioned by the CGSE at UoN and is supported by six other universities. The new facility will be operational by the end of 2014 and will provide Australian geotechnical research groups with mobile state-of-the-art field-testing facilities. Equipment essential to the research of these groups will provide real data on the behaviour of soft soils that are required for the development and calibration of new theoretical design models. The new facility will enable the development of the next generation of *in situ* testing devices, support field testing activities, and will lead to improved interpretation methods. This research will advance the design of infrastructure, such as roads and railways, which are increasingly being routed across soft estuarine deposits.

The new mobile testing facility comprises a customised 120 kN cabin crawler and transport truck (Figure 5). The crawler-mounted *in situ* testing rig provides the same high production and reliability as a truck-mounted rig but with the advantage of tracks, allowing for reduced ground pressure, increased traction and access to soft and difficult terrain. The customised rig is based on a standard cabin crawler design and has been modified to allow testing in conjunction with the transport truck, utilising the weight of the truck, thus providing additional counterweight and saving deployment time at sites where truck access is feasible. The sub-frame of the crawler has been modified to accommodate an enlarged testing opening in the floor of the rig, permit the use of wider devices and allow for non-standard testing. The chassis of the crawler has also been customised to allow the attachment of a hydraulic jack that can be used to apply horizontal loads for experimental research activities, such as the lateral loading of screw piles. The rig will also be modified for its role as a mobile soft soil *in situ* testing laboratory with a fit-out to accommodate enhanced data logging capabilities and permit the addition of precision-control drive systems.

In addition to the conventional hydraulic pushing system, the new facility has been designed to accommodate a separate load frame that allows for the fine control of vertical and torsional actuation using an independent electric drive system. The drive system will allow for the fine control of the penetration rate and torsional rotation, with displacement rates significantly slower than conventional rates. Such slow rates are not possible with conventional hydraulic pushing systems or vane shear rotation systems. To investigate drained-undrained transition behaviour, which is the main benefit of variable-rate testing, speeds down to 0.001 mm/s are required for testing soft clay. To achieve such speeds, a separate electrical drive system and reaction frame will be developed that can be disconnected from the main penetration system. The main penetration system will be used to drive instruments to the proposed test depth and the second system will be used to provide fine control over vertical or torsional displacements at rates as low as 0.001 mm/s and 1000 h per revolution. The actuator control system will be operated using Labview based software in conjunction with electrical stepper motors, drawing on the existing UWA centrifuge technology (De Catania *et al.*, 2010). The system will be designed to enable pre-programmed load or displacement-controlled sequences, thus providing the ability to undertake such novel testing routines as constant-load and cyclic-penetration testing as well as other non-standard activities such as model foundation tests under the rig.

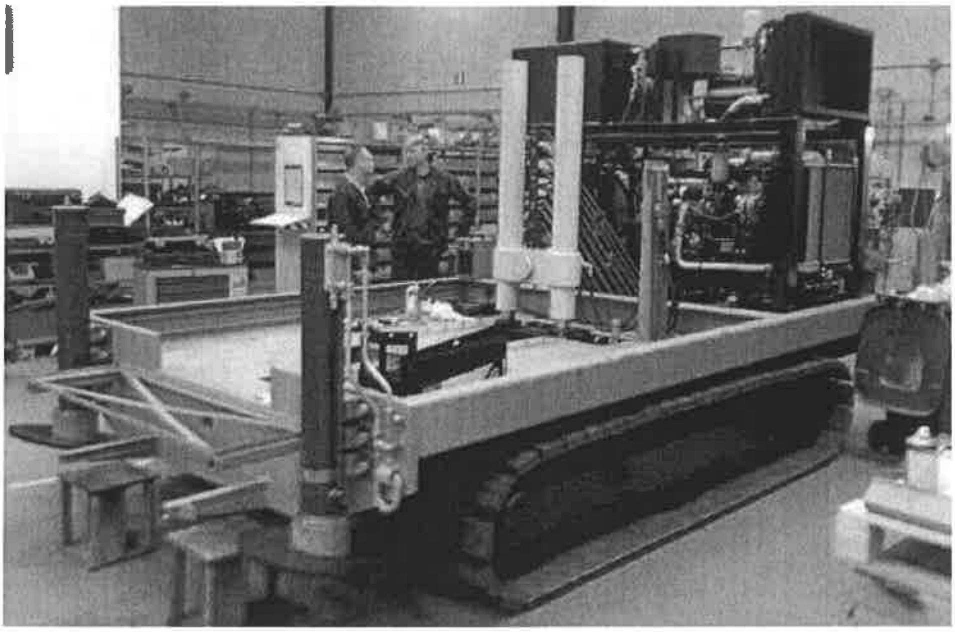

Figure 5: New mobile testing facility being built

Commercial penetrometer data acquisition systems are generally quite restrictive in their application because they are typically only designed to log data for routine tests and are generally only compatible with standard penetrometer equipment. Measurements that are required to undertake non-routine research type testing, such as logging programmed penetrometer motion sequences or variable speed penetrations, are not achievable using conventional CPT data acquisition systems. A separate generic data acquisition system will be implemented into the facility to allow for non-conventional measurements. The new data acquisition system will also provide the ability to operate non-conventional devices such as Piezoballs that include multiple pore pressure sensors. The flexibility gained with a generic data acquisition system is essential for the facility to undertake testing with new and novel penetrometer devices that may be developed in the future. This data acquisition system will also allow for the addition of generic sensors such as displacement transducers and pore pressure sensors which may be monitored, for example during pile load testing.

In addition to the generic data acquisition system described above, a separate remote high speed data acquisition system that operates by communicating back to a base station on the crawler via wireless Ethernet is to be incorporated into the facility. The remote data acquisition system, which was developed by the UWA (Gaudin *et al.*, 2009), will enable the monitoring of up to 50 sensors. The software can remotely control acquisition (such as excitation voltages, signal amplification and logging rates), thereby enabling the crawler to become a mobile laboratory for undertaking various field tests; for example, the system can be used to remotely measure pile-driving or construction activities.

The CGSE, with the support of the Roads and Maritime Services of NSW and industry partners Coffey Geotechnics and Douglas Partners, has established Australia's first large scale soft clay testing site on the North Coast of NSW near the township of Ballina. The test site was initially opened in 2012 and work to date has included the detailed site investigation and construction of two trial embankments, as described elsewhere in this issue (Kelly *et al.*, 2014, Li *et al.*, 2014). The test site provides an opportunity for the compilation and comparison of *in situ* and laboratory tests as well as pilot studies using new site investigation technologies and will establish an extensive database for the mechanical behaviour of soft clay. The new mobile testing facility will have an essential role in the future activities on the test site by providing *in situ* measurements of soil properties before and after various field tests or soil treatments. Moreover, the test site and *in situ* testing facility combination will provide a means for researchers to perform experimental measurements using new *in situ* testing devices and techniques and investigate new interpretation methods on a site at which an extensive database of soil properties exists. The research undertaken with the new national test site will include an investigation of various ground improvement techniques and field scale foundation tests. The knowledge gained from these field tests will benefit industry greatly by identifying improved methods for soft soil treatment for future infrastructure projects and will lead to more robust and economical designs for major infrastructure founded on soft soils.

4 NATIONAL FACILITY FOR CYCLIC TESTING OF HIGH-SPEED RAIL

4.1 EXISTING FACILITIES

UOW has unique facilities to conduct extensive laboratory testing of track components, including ballasts, sub-ballasts, subgrades and shock mats. To study ballast behaviour using conventional small equipment, particles must be scaled down in size, which can lead to misleading results. Therefore, UOW has designed and built two large-scale dynamic triaxial apparatus (LSDTA, diameter = 0.3 m, height = 0.6 m) and process simulation triaxial chambers (PSTC, length = 0.8 m, width = 0.6 m, height = 0.6 m) to test prototype ballast aggregates (scale ratio > 7). These test rigs with dynamic actuators are capable of applying a frequency as high as 40 Hz (Figure 6), and the volume changes of the specimen can be recorded directly by a special measuring device in the LSDTA (Indraratna, 1996) and by movement of lateral walls in the PSTC (Indraratna and Salim, 2003).

Impact loads with very high magnitudes but relatively short durations are induced by wheel-rail irregularities. To assess the behaviour of ballast under impact loads, high-capacity drop weight impact testing equipment (Figure 7) can be used, consisting of a free-fall hammer with a weight of 5.81 kN that can be dropped from a maximum height of 6 m, guided through rollers on the vertical columns fixed to the strong isolated floor (Kaewunruen and Remennikov, 2008). The strong floor consists of a 5 × 3 × 2.5 m concrete mass underlain by a compacted sand layer. The impact equipment can accommodate a test specimen within a working area of 1.8 × 5 m. The impact loads are monitored by a dynamic load cell (capacity of 1200 kN) mounted on the drop hammer and connected to a computer-controlled data acquisition system. Piezoelectric accelerometers (range 10,000 g) connected to the test specimen can record shock events. The typical magnitude of an impact load usually varies between 50 kN and 750 kN, depending on the nature of wheel-rail irregularities and the train speed. Thus, the required drop height and number of impact blows are determined by simulating a typical wheel-flat or dipped rail joint (Nimbalkar *et al.*, 2012).

4.2 NATIONAL FACILITY FOR CYCLIC TESTING OF HIGH-SPEED RAIL (FCTHSR)

The Centre for Geomechanics and Railway Engineering at the UOW, collaborating with several other universities (University of Newcastle, University of Western Australia, University of Melbourne, University of Western Sydney, Swinburne University of Technology, Queensland University of Technology, University of Queensland, University of New South Wales, Curtin University of Technology, Monash University, University of Technology, Sydney) and one industry partner (Metro Trains Melbourne Pty Ltd), has recently secured $1.7M through Australian Research Council's LIEF (Linkage Infrastructure, Equipment and Facilities) scheme for establishing a national facility for the cyclic testing of high-speed rail. Through extensive physical modelling and performance monitoring, this unique national facility will provide improved safety, speed and passenger comfort as well as greater efficiency in long-distance freight mobility.

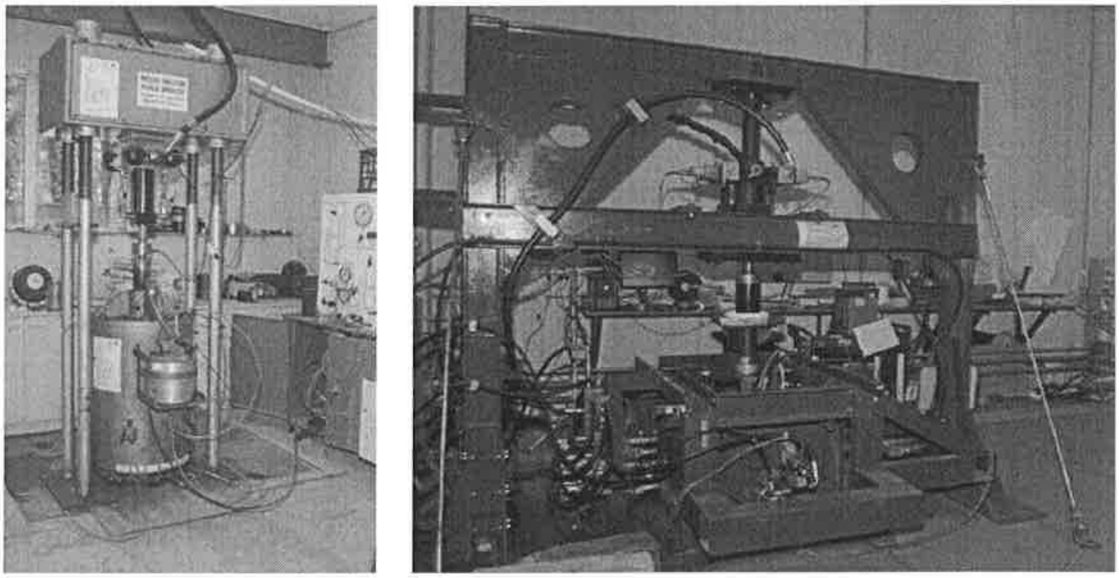

Figure 6: Large triaxial rigs with a dynamic actuator designed and built at UOW.

Figure 7: Drop weight impact testing equipment.

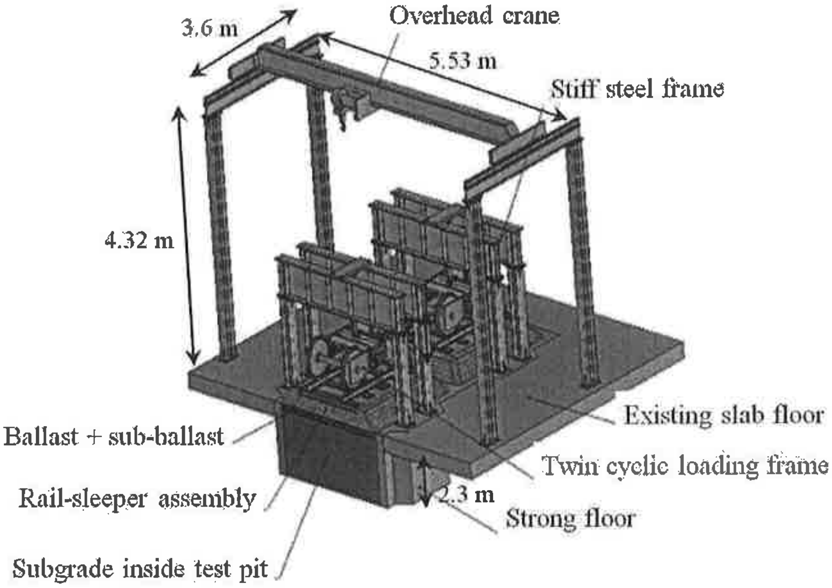

Figure 8: National Facility for Cyclic Testing of High-Speed Rail (FCTHSR).

The national facility will be installed at Russell Vale and is planned to be commissioned by mid-2015. The FCTHSR represents a prototype scale fully instrumented track subjected to dynamic loading actuators that enable the accurate estimation of real life stress-strain response. The maximum height of the facility will be 4.32 m above floor level (Figure 8). Track materials (such as ballast, sub-ballast, subgrade, geosynthetics and shock mats) will be placed beneath the rail-sleeper assembly, which consists of two test pits, loading frame, hydraulic servo system with dynamic actuator, high-capacity power supply system, an instrumentation and data acquisition system and an overhead movable crane with a 5-tonne capacity. The hydraulic system will be customised to apply cyclic loading equivalent to that of 40 tonnes axle trains travelling at speeds of up to 350 km/h. The advanced instrumentation and data acquisition system is being

designed with digital transducers and optical sensors. With axle loads of up to 40 tonnes and a frequency range of 15-60 Hz, representing train speeds of approximately 75-350 km/h, the proposed facility can accommodate a range of cyclic loading patterns and material properties to evaluate track performance under different structural and geotechnical conditions.

Although extensive research has been conducted on individual track components, there have been few efforts toward the performance verification of composite tracks subjected to different ground and loading conditions. Conventional techniques suffer from various major limitations, and scale effects are often difficult to quantify. The ability to accurately predict overall track performance is inhibited by the lack of appreciation of track interfaces and the complex interaction between the track components. The proposed new facility will:

- Create new areas of research that are of significant economic interest to Australia using large physical models with extensive instrumentation and monitoring systems;
- Enhance the ability of major research consortiums, namely the ARC-CGSE and the CRC for Rail Manufacturing (RM-CRC), to launch new state-of-the-art research programs, building on their existing ARC-, CRC- and industry-funded initiatives;
- Provide a genuine vehicle for collaboration among research groups at participating universities;
- Encourage the Australian rail industry to undertake advanced research that will enable troubleshooting of specific problematic track conditions and/or study the performance of new track materials.

The new areas of research evolving using this facility include:

- The investigation of ballast breakage under high speed cyclic loads and extreme impact;
- Analysis of the response of concrete sleepers to extreme loads under high speeds;
- Assessment of effectiveness of synthetic geo-inclusions for improved track stability;
- Vibration mitigation of carriage-track-foundation interactions;
- Advanced sensor technology for in-service structural health monitoring of tracks.

UOW and UON researchers are currently collaborating to determine the cyclic load deformation response of rail tracks and to accurately simulate the adverse impact loads at the wheel-rail interface, capturing the complex mechanisms of ballast breakage and plastic shakedown at increased speeds. Numerical predictions have been calibrated with large scale laboratory testing and field data from the towns of Singleton, Sandgate and Bulli. Upon commissioning of the FCTHSR, the strength and deformation properties of track infrastructure under dynamic and seismic loading will be ascertained under a broad range of cyclic loads and frequencies. Keen collaboration among UOW, UWA, UON, QUT and UTS researchers is expected to yield new technical specifications and guidelines that are absent in Australian rail standards today.

In summary, this unique and world-class test facility will enable Australian researchers to simulate more realistic track conditions in a controlled laboratory environment and will facilitate innovative designs for enhanced track capacity at significantly elevated speeds, generating economies of scale in mixed-freight and commuter traffic, as well as ensure increased track longevity and reduced costs of maintenance.

5 CONCLUSIONS

This paper has described three new physical modelling testing facilities that are being established under the umbrella of the ARC Centre of Excellence for Geotechnical Science and Engineering (CGSE). These facilities include a new 10 m diameter 240 g-tonne fixed-arm beam centrifuge that will be used to maintain correct scaling between large geotechnical footings and infrastructure and their small scale laboratory models. The NewSyd cone truck, already used extensively on Australia's east coast, will also receive a significant upgrade. With the field testing station at Ballina in Northern New South Wales, this development is an advancement of Australia's large-scale testing facilities for soft clay soils. The paper also describes a new prototype-scale fully instrumented rail track for the cyclic testing of high-speed rail infrastructure, including ballast breaking, response of concrete sleepers, assessment of the effectiveness of synthetic geo-inclusions to improve track stability and vibration measurements. The overarching aim of the development of this infrastructure is to provide the Australian geotechnical research and engineering communities with state-of-the-art physical modelling facilities to underpin economic and safe infrastructure developments in our future.

6 ACKNOWLEDGEMENTS

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