IMPACT FROM SYMBIOTIC COLLABORATION BETWEEN INDUSTRY AND ACADEMIA IN OFFSHORE GEOTECHNICS

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ABSTRACT

Offshore geotechnical engineering is often considered to be 'industry leading' with respect to evolving new scientifically based design approaches for foundations and other infrastructure. A high proportion of such advances have originated from collaboration between the offshore industry and academia and, indeed, academic staff in geotechnics at the University of Western Australia have had a particularly significant impact on offshore geotechnical design practice, both locally and internationally, extending over the last 30 years. The nature of interactions with industry and the type of research methodology has varied considerably, ranging from classical doctoral research leading to a major new design approach for a generic problem, to project-specific studies initiated by industry to provide a design basis for particular seabed infrastructure. An example of the former is CPT-based estimation of axial pile capacity in sand, where the UWA approach was incorporated, initially as an alternative to traditional practice but recently as the primary approach, into international guidelines. As a contrast, project-specific studies have often involved physical model tests using the National Geotechnical Centrifuge Facility or the closed O-tube apparatus, to generate data from which to formulate or validate design approaches for a current offshore development. The paper provides examples of these different types of collaboration and their impact on practice, but also discusses the mutual benefits of working with industry, both from a professional perspective for individual academic staff and at the more fundamental level of building and sustaining an economically viable research group.

1 INTRODUCTION

Oil and gas started to be recovered from Bass Strait, in Australia's south-east, in the 1970s, where significant quantities of crude oil were found. While several academic staff at UWA have had intermittent involvement with platform developments in Bass Strait, the main focus here is on the North-West Shelf and Timor Sea in the north of Western Australia, where gas has tended to dominate along with light weight condensates. The first offshore oil and gas platform on the North-West Shelf was Woodside's ill-fated (from a foundation perspective, Senders et al., 2013) North Rankin A platform, which started production in 1984. Since then, nearly 100 separate facilities have been developed, but with an enormous burst of major projects developed concurrently over the period 2000-2015, including Gorgon, Jansz, Pluto, Wheatstone and - in the Timor Sea - Ichthys and Prelude, with others such as Barossa, Browse, Crux and Scarborough currently at different stages of feasibility assessment and front end engineering design. While the early platforms were fixed to the seabed in water depths of up to about 130 m, they were soon joined by deeper water floating facilities, particularly where the fields contained significant quantities of oil. A step change in water depths for new discoveries occurred in the first part of this century with the development of the Greater Gorgon field, operated by Chevron, which comprises reservoirs towards the edge of the continental shelf break in 200 m of water, but also the Jansz and Io fields beyond the shelf break at ~1200 m water depth.

The 'local' offshore oil and gas industry provided exciting research opportunities for academic staff in geotechnical engineering, both at the fundamental level of understanding the response the carbonate sediments that comprise the seabed and quantifying interaction parameters for different types of foundations and anchors, but also more project-oriented applied research to address specific technical challenges emanating from the oil and gas operating companies. It was therefore natural for the geomechanics group at UWA to grow in response to offshore developments; this paper attempts to document some of those interactions, discussing the range of impact with the industry, the evolution of application areas and philosophical musings on sustaining research groups through vicissitudes of university politics, global economy and climate change.

The underlying research strategy has been to pursue a balance of fundamental scientific research, generally funded through commonwealth competitive grants, with more directly applied research typically funded by industry (see Figure 1). From an academic perspective, the most valuable form of industry funding is through medium term (two to five year) collaborations, often in partnership among different companies - so called joint industry projects (JIPs) - or with state of commonwealth contributions such as through Australian Research Council (ARC) linkage projects or the more recent ARC transformational hubs. However, shorter term funding arising from a particular company's challenges on a specific development is more typical and is especially important in the early stages of building relationships. In the engineering field, it is also extremely valuable for academic staff to become involved in consulting, facing the necessity of making design decisions and in many cases revealing gaps in knowledge or understanding that prompt additional fundamental research initiatives. As individuals, requests for consultancy arise through national and international reputation and can be somewhat sporadic in nature, particularly in early career. An alternative approach followed by some staff at UWA has been to enter into consulting arrangements with particular companies, which generally leads to more continuous consultancy work and also a greater awareness of opportunities for additional engagement.

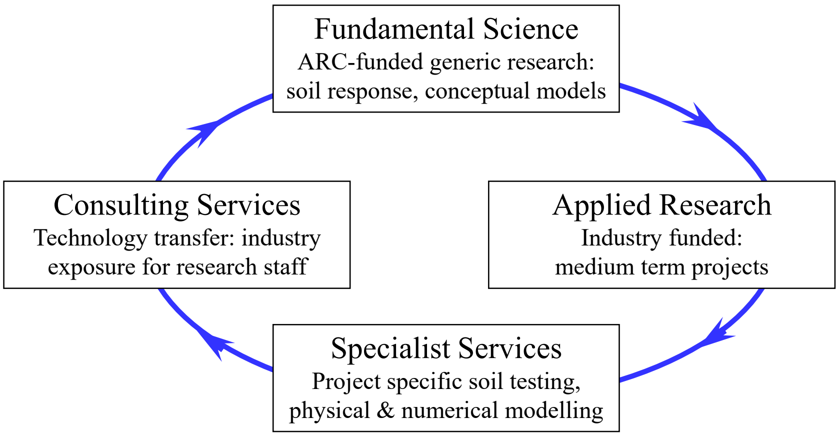


Figure 1 Research strategy

As may be inferred, interactions with industry have the double benefit of generating funding to sustain a group, for example with respect to funding PhD studentships and project costs and early career academic staff or to maintain and develop experimental facilities, but also achieving a level of impact that is ultimately more satisfying and valuable than through publications alone. In all aspects, balance is essential: consultancy must be undertaken within policy guidelines of the university, maintaining primary focus on core teaching and research commitments and avoiding any perception outside the university of undercutting potentially competing consultancies; similarly, industry use of experimental facilities should be charged at a commercial level that covers all infrastructure, maintenance and development costs. In most cases, experimental facilities will also be needed for postgraduate (and occasionally undergraduate) project work or for different research grants, so requests by industry must be scheduled among a range of competing work. This aspect is discussed in more detail later.

2 SUSTAINED COMMONWEALTH FUNDING

2.1 ARC CENTRES OF EXCELLENCE

The cornerstone of sustainability of offshore geotechnical engineering at UWA has been a series of significant 'platform' grants from the ARC. The first of these established the ARC Special Research Centre for Offshore Foundation Systems (COFS) in 1997, which included a node at Sydney University led by Professor John Carter. Key staff at UWA included Mark Randolph (Director), Richard Jewell and Martin Fahey, together with early career academic staff supported by other funding, including at the time Fraser Bransby and Yuxia Hu. COFS was also supported by two grants from the WA State Government, one of which supported the establishment of a high-quality soil testing laboratory and the second, coming at the end of the ARC funding of COFS in 2005, facilitated the transition of COFS to research relevant for deep water developments. The COFS Directorship at this stage transitioned to Mark Cassidy, who in 2010, assisted Professor Scott Sloan in creating the ARC Centre of Excellence in Geotechnical Science and Engineering, based at Newcastle University, in which COFS was the second primary node. The ARC Centre of Excellence coincided with a period of high activity in the oil and gas industry that promoted the development of parallel funding initiatives supporting the growth of the centre. This includes the establishment of: the Chair in Offshore Engineering funded by Shell in 2012 initially held by David White; the ARC Industry Transformational Research Hub for Offshore Floating Facilities by David White in 2015; and the National Geotechnical Centrifuge Facility by Christophe Gaudin in 2016. All these initiatives contributed to broaden the scope of activities undertaken by the UWA group, to secure the position of key young academics who would later take a leadership role in the centre and to strengthen engagement with the local and international industry. They are discussed in more detail later.

The ARC Centre of Excellence in Geotechnical Science and Engineering finished in 2017, at which point, restructure within UWA saw COFS leading the creation of a multidisciplinary ocean engineering group within the Oceans Graduate School (OGS). COFS is currently led by Christophe Gaudin and remains fully active in offshore geotechnics with 11 full time academics and over 20 PhD students. Financial support is provided through a mix of university funding for established positions and a range of income from competitive grants and industry.

2.2 ARC TRANSFORMATIONAL HUBS

The Industrial Transformation Research Program is a relatively new programme and encourages collaborative research through value-oriented partnering of industry and university-based researchers. As part of this program, the *Research Hubs* are strategically chosen to pursue outcomes that cannot be realised independently and which will support national interest in key sectors – including energy resources.

The Offshore Floating Facilities Research Hub (OFFshore Hub, www.offshorehub.com) was funded in 2014, led by David White and subsequently directed by Phil Watson from 2017, and aligns with a shift in offshore infrastructure towards deep water developments that incorporate large – sometimes permanently manned – floating facilities and expansive subsea infrastructure. The Shell Prelude FLNG off northwest Western Australia, which itself is the world's largest vessel, typifies this and the need to focus on emerging engineering challenges associated with deep water developments. Industry partners in the OFFshore Hub were Shell and Woodside, with the latter operating a number of floating assets on the Northwest Shelf, as well as Lloyds Register and Bureau Veritas. The direct inclusion of certification bodies in the program was to facilitate translation of research outcomes into codes of practice for industry adoption.

For the geotechnics team at UWA, the OFFshore Hub represented a step towards true multi-disciplinary research, with collaboration across discipline areas enabling more impactful industry challenges to be tackled. The program included research in ocean behaviour and forecasting, vessel motion and offloading, riser and mooring design, novel anchors and subsea foundations, and data analytics for response prediction and facility longevity; the activities comprised a blend of physical and numerical modelling, supported by fieldwork and the analysis of observations from existing facilities. A follow-up ARC Research Hub - Transforming energy Infrastructure through Digital Engineering (TIDE) led by Phil Watson – was awarded in 2020 and will further expand the multi-disciplinary nature of offshore research (see later).

2.3 WAVE ENERGY – ARENA PROJECT AND WERC

Historically COFS has collaborated extensively with the consulting industry and the oil and gas majors through the support of ARC funding schemes. Over the last decade, COFS has diversified its industry engagement and support mechanisms, in particular by exploring opportunities within the offshore renewable energy space. This was motivated by (i) opportunities created by engagement with a larger multidisciplinary ocean engineering group within the OGS, (ii) the interest and willingness to champion and accompany our traditional partners through the transition towards renewable energy and (iii) the need to diversify its support portfolio, acknowledging that the large ARC schemes are not yet aligned to support large scale research on offshore renewable energy.

Two current initiatives are related to wave energy, with one project supported by the Australian Renewable Energy Agency (ARENA) and the other by the Department of Primary Industry and Regional Development within the WA State Government. In both cases, the duration of the project (4 years) and the level of funding ($1M and $3.75M, respectively) enabled the appointment of early career researchers and PhD students, consolidating activities within COFS, but also expanding them at the interface with oceanography and hydrodynamics, in parallel to similar developments within the ARC ITRH OFFshore Hub (e.g. Rijnsdorp et al. 2020).

These funding schemes have also broadened the network of industry partnership, outreaching to SMEs domestically and internationally, shaping a new form of collaboration. The strategy remains the same as that presented in Figure 1 but the engagement and support are tailored to acknowledge the specific requirements of SMEs, notably associated with their size and the level of development of their technology. The engagement has also evolved to include the funding partners in the collaboration, which often have requirements and expectations different from those of the ARC. The output and impact are no longer concentrated solely on the development of geotechnical solutions, but also include the formulation of future geotechnical challenges to be addressed, as well as educational outreach and networking activities.

3 MEDIUM TERM INDUSTRY PROJECTS

3.1 INDUSTRY FUNDED CHAIRS

COFS has benefited from direct industry support through industry funded Chairs, all of which have facilitated impact through focused transfer of research outcomes into practice.

Lloyd's Register Chair and Centre of Excellence for Offshore Foundations

In 2010 COFS partnered with the Lloyd's Register Foundation (LRF) to establish the LRF Chair in Offshore Foundations and Research Centre of Excellence to carry out at the highest international standard fundamental and applied research in the areas of seabed sediment, offshore geohazards and in offshore foundations and energy systems, to use its expertise to service the offshore petroleum and renewable energy industries at both a national and international level, and to create research outcomes that improve the safety, viability and reliability of offshore energy developments. Initially covering a five-year funding period, the Centre of Excellence was extended until 2019 and over this time supported 15 PhD students. The Chair was initially held by Mark Cassidy, before transitioning to Britta Bienen in 2018.

Impact of this Centre of Excellence includes incorporation of our research into guidelines (e.g. ISO 19905-1, Zhang et al., 2012a,b, 2013, 2014; and the first guideline for suction buckets supporting offshore wind turbines developed under the Carbon Trust, UK, Bienen et al. 2018a,b, Zhu et al. 2018), development of software that is used by the offshore industry and knowledge transfer through dissemination of research findings directly to industry partners, with companies such as COWI, DEME, Ørsted, Rambøll and Royal IHC using our research findings. Impact was also achieved through public outreach such as the LRF Orations, free public lectures that have attracted colleagues from academia and industry alike year after year, providing valuable networking opportunities. Active membership of the International Organization for Standardization (ISO) represents another pathway of engagement and impact.

The sustained partnership with LRF supported a transition in research focus to offshore renewable energy (see also the later section on evolution of research focus) and made a major contribution to building and sustaining a research group and translating applied research to impact.

Shell Chair in Offshore Engineering

Shell has been involved in offshore energy in Australia since the very early days as a partner in the sector-defining North West Shelf Joint Venture. The subsequent decision to develop (as operator) the Prelude gas field using Floating Liquefied Natural Gas (FLNG) technology saw an increased presence in Australia and, as part of this, the decision to invest in UWA via the Shell Chair (then 'Shell EMI Chair') in Offshore Engineering – with the aim to strengthen UWA and Western Australia's position as a global offshore engineering hub, through world class research and education. Funded by Shell and UWA, the program supports the activity of multiple researchers. The inaugural Shell Professor was David White, who was succeeded by Phil Watson in 2017.

Much of the research activity is defined in partnership with Shell engineers, based both in Perth and around the world. The research is multi-disciplinary in nature, broadly aligned to the activities of the Oceans Graduate School. Significant activity has been undertaken in relation to Prelude FLNG, including contributing to a WA Parliamentary Inquiry into safety aspects of FLNG, and efforts to define and forecast the metocean environment surrounding Prelude and understand its impact on (predominantly offloading) operations. Geotechnical projects include studies into the aging of offshore piles to justify life extension or increases in load carrying capacity; testing to support the commercialisation (by Shell and partner Subcon) of their pipe-clamping mattress technology used to arrest pipeline walking; and an increasing number of projects related to design of foundations for offshore renewable infrastructure, all of which reflect an increasing investment in this area by Shell.

Fugro Chair in Geotechnics

The piling difficulties encountered in construction of the North Rankin A and Goodwyn A platforms (e.g. Senders et al. 2013) (i) showed the importance of managing the risk of the seabed appropriately and (ii) suggested that specific (local) geotechnical knowledge about the regional carbonate seabed properties needed to be applied to design. Geotechnical consultancy Advanced Geomechanics (AG) was formed in 1994 under the leadership of Mohamed Khorshid (ex-Woodside) with the aim of filling this gap by combining skills from experienced local practitioners (e.g. founding Directors Khorshid and Paul Hefer) with those from the UWA geotechnics group (e.g. founding Directors Randolph, Fahey and Jewell, later joined by John Carter from Sydney University). AG was successful commercially and grew symbiotically with the UWA geomechanics group (and the burgeoning local oil and gas market) so that by 2013, both COFS and AG each comprised about 70 members. This symbiosis took the form of AG employing a large number of UWA PhD graduates, UWA staff providing geotechnical consultancy through AG and UWA providing project-specific testing (through soil element testing, centrifuge model testing and scour element testing) for AG, all of which led naturally to close links between the two organisations. This was beneficial to UWA through the generation of research ideas, the generation of testing income and through providing a mechanism of impacting directly on practice.

Advanced Geomechanics was acquired by Fugro in 2013 and became part of a global geoconsulting team led by Phil Watson (transition from his role as Managing Director of AG) before his return to UWA. Given the importance of the link to both parties and to help spread this globally to other teams within Fugro, the Fugro Chair in Geotechnics was inaugurated by Fugro within a year of the acquisition of AG, funded for a 6-year term. In December 2014, Mark Randolph was appointed as the inaugural Chair, reflecting his joint history in both organisations and his global profile in the field of offshore geotechnics. The Chair, currently held by Fraser Bransby, continues to link the two organisations symbiotically, whilst having the flexibility to move focus towards the growing global renewable energy markets and its associated challenges in site characterisation, and foundation and anchor design (e.g. Low et al., 2020, 2021).

3.2 MULTI-YEAR JOINT INDUSTRY PROJECTS AND ARC LINKAGE PROJECTS

Over the last twenty-five years, several joint industry projects (JIPs) have been undertaken, focusing on new technical and design developments of interest to the industry partners. Two of these were negotiated through MERIWA (Minerals and Energy Institute of WA) who also provided collaborative funding. In the 1990s, new types of offshore foundations were envisaged as an alternative to traditional piled foundation. This led to a project with industry partners Woodside and West Australian Petroleum (now part of Chevron) that included a study of caisson foundations in addition to streams on basic properties of deepwater calcareous silt and the response of laterally loaded piles. The second MERIWA project, with industry partners BHP Billiton, BP, Chevron, Petrobras, Shell and Woodside, supported the evolution of COFS from shallow water applications to deep water. The project spanned streams on submarine landslide geohazards, debris impact of seabed infrastructure and large deformation finite element analysis of debris flow (White et al., 2016). Complementary funding from the WA State Government was crucial in helping to bridge the gap between the two ARC Centres of Excellence grants, the first having finished in 2005 and the second starting in 2011.

Other notable JIPs were two that were negotiated in conjunction with the Norwegian Geotechnical Institute (NGI), managed by Tom Lunne and sponsored initially by BP, Conoco, Norsk Hydro, Statoil and Woodside, and in a second phase by oil and gas companies BG, BP, Chevron, Exxonmobil, Shell, Statoil, Total and Woodside joined by contractors Benthic, Fugro, Geo, Lankelma, Seacore, Subsea 7 and TL Geosciences. The JIP focused on the characterisation of soft sediments in deepwater sites with offshore and onshore SI data from full flow penetrometers (T-bar and ball, Figure 2) in addition to piezocone tests. In many ways the project marked the maturation of T-bar and ball penetrometers that were originally developed as tools for the centrifuge to characterise clay samples (Stewart et al. 1991), providing best practice testing and interpretation methodologies (Low et al., 2010, 2011; Lunne et al., 2011).

(a) Penetrometers (b) Example monotonic and cyclic T-bar data

Figure 2 Cone, T-bar and T-bar penetrometers and example T-bar data from Jansz

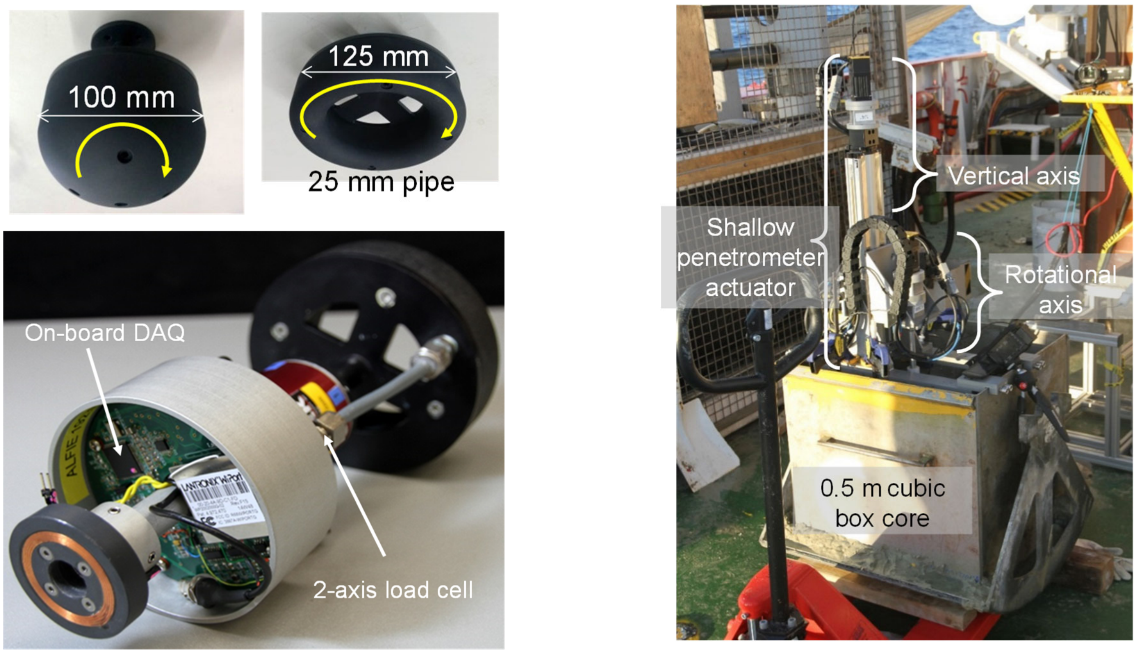
In 2008 a JIP was formed to reassess the stability design of on-bottom pipelines, known as the STABLEpipe JIP. The initial phase of this work was led by JP Kenny (now Wood), who recommended the need for large scale testing to properly investigate the effect of sediment mobility on pipeline stability. In parallel, Woodside and UWA developed the O-Tube flume (described later in this paper), which was subsequently used in two additional phases of research, led by Liang Cheng and David White, with funding from both Woodside and Chevron and technical input from JP Kenny. The JIP ultimately led to the development of new design guidelines co-authored with Det Norske Veritas (now DNV GL) (Griffiths et al., 2018).

The InSafeJIP (2009-2011) with 19 project sponsors including ExxonMobil, Shell, DONG Energy (now Ørsted), Maersk Drilling and academic collaborators at the National University of Singapore (Kar Lu Teh and Colin Leung) and the University of Oxford (Guy Houlsby) aimed at improving the prediction of jack-up installation and removal through benchmarking of recent research developments against field data. Recommendations from the InSafe JIP (Osborne et el.

2009) now form an Annex to the ISO 19905-1 guidelines. The JIP provided valuable opportunities for direct knowledge transfer between industry and academia and established vital networks for the then early career researchers Britta Bienen and Shazzad Hossain, which translated to numerous further opportunities.

More recently (2013-2018) new shallow embedment site investigation tools targeting pipeline design were developed through the RIGSS project, led by David White and sponsored by Fugro, Shell, Total and Woodside. The main innovation from the project was the development of axisymmetric torsional penetrometers, toroidal or hemi-spherical together with very precise control of rotation or torque and vertical load or displacement, see Figure 3 (Schneider et al., 2020a,b,c). The device is able to measure the frictional response at the interface with the soil under monotonic and cyclic loading. Aspects such as pore pressure development and the subsequent effects of consolidation can be quantified, with direct application to the axial response of pipelines. The devices have already been implemented into site investigation studies conducted offshore by the companies involved in the JIP.

In parallel with JIPs, several ARC Linkage projects have been undertaken. While the funding mechanism is different, the intent remains the same and enables close partnerships over a sustained period to develop practical solutions. Notable Linkage and other partnerships include Keppel on spudcan direct design from CPT data and hybrid foundation performance, Lloyd’s Register Foundation on offshore wind turbine foundation and Carnegie Clean Energy on wave energy converter hydrodynamics and anchoring. A notable example of how the Linkage scheme can lead to long term collaboration was successive projects (LP140100066, LP170101080, led by Shazzad Hossain and Youngho Kim) partnered with Daewoo Shipbuilding and Marine Eng. and Daewoo Engineering and Construction in South Korea. These have led to a range of consultancy projects, exchange visits, joint venture testing, workshops and training secondments in COFS involving these companies and others including Foresys, GS EandC Corp., Posco Steel Solutions and Samsung Heavy Industries.



(a) Penetrometers and actuator

(b) On-board set-up for testing box-cores

Figure 3 Torsional hemiball and toroidal penetrometers for offshore testing of box-cores

4 EXPERIMENTAL FACILITIES

4.1 NATIONAL GEOTECHNICAL CENTRIFUGE FACILITY (NGCF)

UWA’s contributions to the field of offshore geotechnics are well recognised internationally, much of which is underpinned by the high-quality experimental work undertaken in UWA’s geotechnical centrifuges. The first (3.6 m diameter) beam centrifuge was installed in UWA in 1988, with the additional of a (1.2 m diameter) drum centrifuge in 1996 and a second (10 m diameter) beam centrifuge in 2016 (Figure 4). Commissioning of the second beam centrifuge coincided with the establishment of the National Geotechnical Centrifuge Facility (NGCF, www.ngcf.edu.au), recognition of the service that UWA’s geotechnical centrifuges have provided to academic and industry communities in Australia and across the globe.

The NGCF, supported by an ARC LIEF grant led by Christophe Gaudin and now directed by Conleth O'Loughlin, operates as a separate business unit within the university, with a financial model based on access charges (for centrifuge spin time and technical services) meeting the approximately $1.5M annual budget. UWA has operated its geotechnical centrifuge facility for three decades and has achieved its reputation for quality by ensuring that the facility is championed by an academic with expertise both in geotechnical centrifuge modelling principles and in offshore geotechnics, and maintaining a dedicated technical team (of research officers, electronic, mechatronic, software and mechanical engineers) with expertise in centrifuge modelling.

As illustrated by research impact examples detailed in the paper, the majority of the geotechnical research undertaken at UWA is in collaboration with industry. This is demonstrated by the breakdown in NGCF incomes (for 2019) shown in Figure 5; the highest revenue stream is centrifuge usage (65%), of which 63% was in collaboration with industry.

Figure 4 The NGCF centrifuges: 3.6 m diameter beam centrifuge (left), 10.0 m diameter beam centrifuge (middle) and 1.2 m diameter drum centrifuge (right)

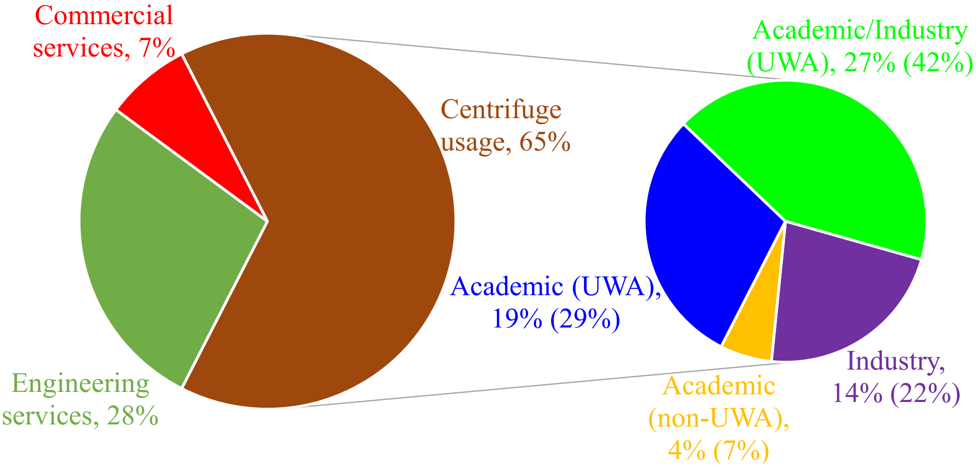


**Figure 5 Breakdown of NGCF incomes (2019 figures).
Percentages in parentheses represent the proportion of centrifuge usage**

4.2 SOIL TESTING LABORATORY

A cornerstone of early COFS research was study of the fundamental engineering properties of carbonate soils, reflecting the significance of this issue to early platform development on the North West Shelf. Understanding the stress-strain behaviour of the seabed sediments aligned with the development of numerical and theoretical models to describe foundation response for incorporation into design practice. At that time, Western Australia lacked the facilities for sophisticated soil element testing, either for research or commercial applications, which provided the rationale for investment in specialist testing facilities. Key achievements included the development of an X-ray system to assess the quality of samples recovered offshore – a practice that continues to this day. In addition, state-of-the-art simple shear and triaxial apparatus to perform advanced testing of carbonate soils were developed in-house, enabling databases of soil behaviour to be compiled both for research and industry purposes.

Rapid investment in the offshore energy sector through the early 2000s saw expansion of the UWA soil laboratory, which played a pivotal role in site characterisation for numerous offshore developments. Ultimately, commercial success in this area – and the impact of increasingly challenging project deadlines - saw the development of Perth's first commercial soil laboratory for advanced testing of offshore soils (Advanced Geomechanics' 'agLAB'). More recently, a second local laboratory (GTI Perth) has been established, with the two laboratories supporting Australian offshore projects and importing specialist testing from overseas. While the transition of advanced soil testing to industry reduced direct industry funding to UWA, it is an excellent example of technology transfer and an enduring legacy of the research group. Today, the UWA soils laboratory continues to provide advanced testing to a range of industry sectors, including the mining and tailings industry, and remains engaged in the development of new equipment, a recent example being the development of specialist apparatus to measure low stress consolidation and compression behaviour.

4.3 O-TUBE

In 2008, Woodside approached Liang Cheng, David White and Mark Randolph to develop an experimental testing facility that could model pipe-soil-fluid interactions at relatively large scale, enabling detailed research into on-bottom pipeline stability. This motivated the construction of the O-Tube, part-funded through the ARC Linkage scheme, in which an enclosed volume of water is moved by an impeller to mimic steady (current) and oscillatory (near bed) water velocities above a sediment bed (see Figure 6). In this way, the O-Tube allows a model pipeline to experience near-seabed flow conditions, such that wave-induced liquefaction and local scour may evolve naturally, concurrent with hydrodynamic loading of the pipeline and the mobilization of soil resistance (An et al., 2013). This unique facility underpinned the STABLEpipe JIP and has been used for numerous project-specific studies since, including the stability assessment of existing pipelines (to support life-extension), new pipeline developments and scour investigations for a range of subsea infrastructure used in both the oil and gas industry and the emerging offshore wind and wave industries. In many of these applications the underlying research has involved a collaboration across geotechnics and hydrodynamics, making use of sensing and control technology developed by the National Geotechnical Centrifuge Facility.

Following its commissioning, the O-Tube had an immediate impact on pipeline engineering design with Woodside, for example, reporting a 10:1 return on their investment in the facility in a note to shareholders within the first few years of its development. In parallel to this success, two smaller O-Tube facilities at UWA have also seen significant use; measuring about 20% in all dimensions compared with the larger O-Tube, the smaller facilities are ideal for erosion testing of sediment samples and for undertaking small scale pilot study experiments and scaling studies. To date, erosion testing in the smaller O-Tubes has informed scour design on almost all of the large-scale developments offshore WA since 2010 in addition to developments in Vietnam, West Africa and the North Sea. The facilities have also been used to pioneer new experimental sensing techniques (An et al., 2017) and to help interpret increasing quantities of field observational data (Yao et al., 2018).

Figure 6 Large O-Tube facility. Right, scour around a model pipeline – current from left (Draper et al., 2015)

5 CASE STUDIES OF IMPACT

The breadth of COFS research activities and the extent of its collaboration with industry has led to significant impact across all types of design challenges, including pile behaviour, anchoring systems, spudcan stability, pipeline-soil interaction, steel catenary risers and shallow foundation behaviour. It is not possible to cover all of these in the paper but a few examples are provided that highlight the importance of research input and testing services in developing innovative solutions.

5.1 PILE FOUNDATIONS

There is a long-standing interest at COFS, and UWA generally, in improving analysis and design methods for piles under general loading conditions. While this has largely been driven by the needs of industry, as clearly illustrated by the piling difficulties experienced at North Rankin A and Goodwyn A in the 1980s, much of the development has evolved simply because of the passion amongst the academics and researchers at UWA in this subject area, many of whom did their PhD on a particular aspect of piling research (including Randolph, Lehane, Bransby, White etc).

Piling engineering is a unique blend of science and empiricism, as reflected in the title of the 43rd Rankine lecture by Randolph (2003). As such, improvement in the state-of-the-art requires the interaction of physical testing, numerical analysis and back-analysis of test data. In addition to centrifuge-based and numerical/analytical studies, the impact of UWA research has also been aided by experimental programmes involving instrumented pile tests at sand and clay sites in the Perth region.

Examples of piling research projects undertaken in the past decade at UWA have examined:

a) the influence of the pile installation method and pile geometry on axial and lateral pile response (of particular interest to the offshore wind industry)
b) long term gains in pile shaft friction (impacting life extension of platforms and reuse of foundations)
c) driving resistance of piles (including methods to assess the potential for tip damage and extrusion buckling)
d) design considerations for screw piles (presently being considered for wind turbines and wave farms)
e) the performance of bored (onshore) and drilled and grouted (offshore) piles.

These and other projects, which have been supported by a combination of Industry and ARC funds as well as national competitive research funding secured through international collaborators (e.g. the long-standing collaborating with TUHH in Germany), have made a significant impact on engineering practice in Australia and worldwide.

One example of the strong interaction between UWA and Industry in the piling area is a joint industry project (JIP) between 2014 and 2021, which was led by Barry Lehane and managed by the Norwegian Geotechnical Institute (NGI) with funding from energy companies including Aramco, BP, EDF, EnBW, Equinor, ExxonMobil, Lundin, ONGC, Ørsted, SSER and Total. The JIP brought together experts from around the world and, following a number of intermediate steps, finally succeeded in getting agreement on the formulation of new design methods for derivation of the axial capacity of driven piles in sands and clays (Lehane et al. 2020, 2021). The method established for derivation of the capacity and load-displacement response of piles in sands is incorporated as the primary design method in the 2021 edition of the International Standards Organisation recommendations (ISO 19901-4) while the clay method is included in the Annex of ISO 19901-4 with good prospects for its promotion to the primary method in due course.

5.2 PIPELINES

The increasing number and scale of offshore projects on the North-West Shelf, particularly from 2005 to 2015 as mentioned earlier, necessitated the construction of long lengths of new pipelines and flowlines in the region. Offshore pipelines can be split mainly into two types: (i) large diameter export pipelines to shore (e.g. Woodsides first and second export lines to the Burrup (1TL, 2TL), Pluto export trunkline, Wheatstone export trunkline, Ichthys Gas Export Pipeline etc.), and (ii) smaller diameter 'in-field' pipelines/flowlines that transport high pressure and high temperature product from wells to gathering structures or platforms nearby. For export pipelines, the main engineering challenge is associated with ensuring hydrodynamic stability of the pipelines during cyclones where they cross long extents of shallow water, or even (as in the case of the export lines from the Jansz field) from deep to shallower water up the continental shelf-break (Zhang et al., 2015 – see Figure 7. For most export pipelines the aim of geotechnical design is to reduce the potentially very large (e.g. $2-4 M/km) costs of primary and secondary stabilisation. For infield pipelines/flowlines, the governing response is the potential for lateral buckling and walking, with design work ensuring that lateral buckling can be tolerated by the pipeline (potentially with the use of buckle initiators) and that walking is minimised (ideally avoiding the expense of holdback anchors).

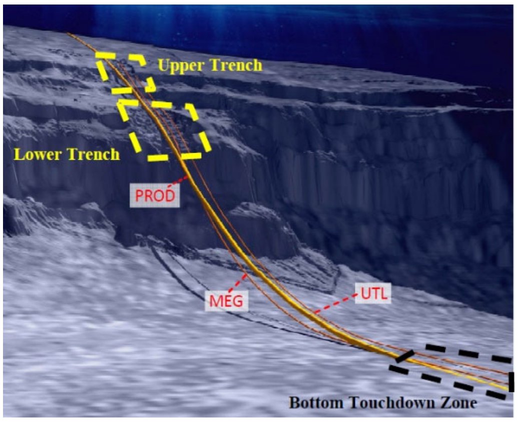


Figure 7 Overview of Gorgon scarp crossing (Zhang et al., 2015)

To address the above issues, UWA has carried out a mix of generic research, often in collaboration with industry, and project-specific testing focusing on improving site investigation for pipelines and improving methods to quantify pipe-soil interaction for given seabed conditions. This has involved:

- Improving pipeline-related site investigation methodology (e.g. White et al., 2015, 2017; Randolph et al., 2018)
- Developing methods to predict approximately the statistical variation in as-laid pipeline embedment for both carbonate and non-carbonate soils (e.g. Westgate et al., 2010, 2012).
- Developing methods to calculate soil resistance to lateral movement using the V-H failure envelope method for undrained soil behaviour (e.g. Merifield et al., 2008) and drained soil behaviour (Tian and Cassidy, 2008).

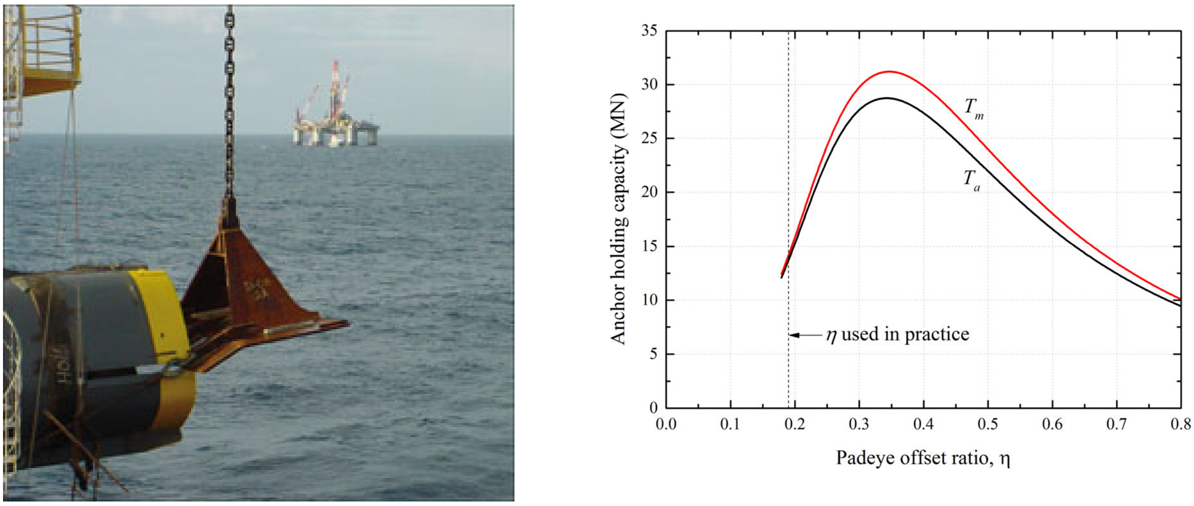
- Conducting project- and site-specific centrifuge model pipe-soil interaction testing in the NGCF (e.g. Gorgon, Pluto, Wheatstone, Browse etc). This involved use of field samples, high quality test control and testing programmes specified by the client (e.g. Bransby et al., 2013) in the NGCF. These results were used directly in multiple projects.
- Involvement in the SAFEBUCK JIP, which was a global project which improved general methodologies to design HTHP pipelines accounting for thermal expansion (and walking) and lateral buckling (e.g. Bruton et al., 2008). The geotechnical methodologies developed (e.g. Chatterjee et al., 2012; White et al., 2012) have made their way to state-of-the-art papers, codes and recommended practice documents (e.g. White et al. 2017), although modifications are required to use some of these methods for the carbonate soils on the NWS (e.g. Bransby et al., 2020).
- Evaluating whether 'live' sediment mobility around a pipeline either before or during a hydrodynamic stability event (e.g. cyclone or soliton) can be 'banked' to reduce secondary stabilisation (e.g. trenching, anchoring, rock-dumping etc.) requirements. As mentioned above, this involved development of the three UWA O-tubes, and their use in the STABLEpipe JIP (Griffiths et al., 2018), for research (e.g. Draper et al., 2015) and for project-specific testing (e.g. project-specific testing in the large O-tube was used to demonstrate the stability of 1TL and remove remediation costs; Jas et al., 2012).
- Considering whether sediment mobility changes in pipeline embedment state between pipe-lay and start-up can make buckling less reliable (e.g. Bransby et al., 2014). A collaborative project with Woodside involving detailed examination of annual inspection surveys for pipelines on the NWS (e.g. Leckie et al., 2015, 2016) and these observations and associated sediment mobility calculation methods have informed design practice changes for projects on the NWS to account for this phenomenon.

All of the above have been applied in projects off the northwest of Australia with most significant economic savings in the A$10 billion offshore pipeline industry.

5.3 PLATE ANCHORS

The term 'plate anchor' includes any anchor where plates or flanges provide the primary resistance, for example the gravity-installed OMNI-Max anchor (Shelton, 2007; Wilde et al., 2001). However, the most common offshore plate anchor is the suction embedded plate anchor (SEPLA), where a suction caisson is used as a mandril to install the plate – see Figure 8a. In order to allow SEPLAs to be used offshore West Africa to anchor floating production vessels over a prolonged period, as opposed to temporary anchoring of drilling rigs, Exxonmobil commissioned COFS to undertake a detailed study involving numerical and physical modelling as the basis for a more robust design approach. While the capacity of a plate anchor in clay of a given shear strength is well established from plasticity solutions, design must consider a number of factors including:

1. loss of embedment during keying (i.e. as the anchor mooring line is tensioned)
2. strain-softening of the soil
3. reduction factor on theoretical bearing capacity due to the plate angle relative to the mooring chain
4. effects of cyclic and sustained loading.



(a) Insertion of plate anchor into caisson tip

(b) Theoretical ultimate anchor holding capacity

Figure 8 Suction embedded plate anchors

The starting point for design is the soil shear strength at the original (known) embedment depth of the anchor (i.e. the depth of the anchor centroid), together with the relevant bearing capacity factor for a rectangular plate of $N_c = 14$. The study showed that each of the factors above successively reduce the design anchor capacity (even ignoring any material factor) by approximately half, from 14 to $N_{c,design} \sim 7\text{-}7.5$ (Wong et al., 2012).

A key outcome from the work for Exxonmobil was an assessment of the role of the keying flap on the SEPLA. Originally conceived to reduce embedment loss as the anchor keys, kinematic evidence from centrifuge tests utilising particle image velocimetry (PIV) measurements (Gaudin et al., 2010) showed that the flap does not activate during keying but after keying is complete, in effect reducing the potential holding capacity through a reduction in the projected area of the plate. These observations triggered several additional UWA studies into SEPLA plate geometry (e.g. Wang et al. 2013; Tian et al. 2015a) that also considered the potential for the SEPLA to move into deeper soil ('dive') when overloaded. This effectively requires that the anchor padeye is offset from the centroid of the anchor. UWA has provided recommendations for a more effective padeye location for SEPLAs (e.g. Tian et al., 2015b) that promotes this diving behaviour and effectively allows for an ultimate anchor capacity that is approximately double that when the padeye is located centrally on the plate (see Figure 8b).

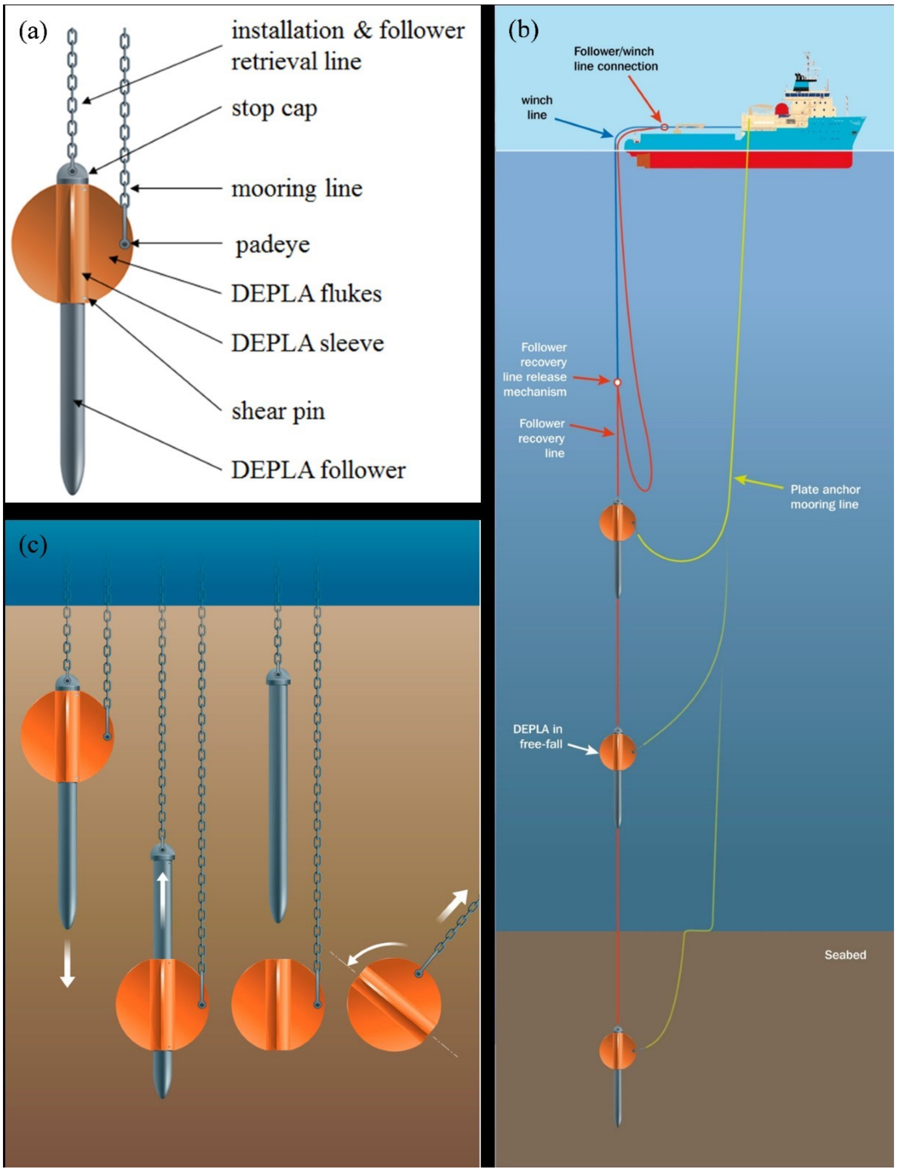


Figure 9 Dynamically embedded plate anchor: (a) annotated schematic, (b) installation procedure, (c) post installation keying and capacity mobilisation

As an alternative to suction installation, plate anchors can be installed dynamically using a free-fall pile rather than a suction caisson as the mandril. This concept arose from UWA work into dynamically installed anchors (e.g. Petrobras's torpedo pile) and led to the development of the dynamically embedded plate anchor (DEPLA), which was licensed by

UWA to Vryhof in 2013. In the DEPLA concept (see Figure 9), the plate anchor is dynamically installed by releasing a dart-shaped object that free falls into the seabed. The central follower of the object is subsequently removed and reused in the next installation, leaving the flukes embedded in the seabed as a plate anchor. Much of the early DEPLA work focused on frameworks for calculating anchor embedment depth and monotonic anchor capacity (e.g. O'Loughlin et al., 2016), calibrated and validated from centrifuge and field data (from reduced scale anchor trials). More recently (e.g. Tom et al., 2021) attention has moved towards establishing reliability for DEPLAs (and by extension to other dynamically installed anchor types), as uncertainty in seabed strength may result in higher reliability for a DEPLA than for a SEPLA as dynamically installed anchors have a self-correcting characteristic. If the soil is weaker than expected a DEPLA will embed further and vice versa, with approximately the same soil strength at the final anchor embedment depth, unlike for a SEPLA where the uncertainty in soil strength carries through to uncertainty in anchor capacity. As for the SEPLA, DEPLA reliability can be further improved by considering the location of the anchor padeye, as shown in recent numerical and analytical work (Tian et al., 2021).

The benefit from dynamically installed torpedo-style anchors has already been proven offshore Brazil and in the Gulf of Mexico. However, their application in silty seabeds, particularly Australian calcareous seabed sediments, has been restricted by the much lower embedment depths achieved during dynamic installation. This led to development of a dynamically installed 'fish' shaped anchor, adopting a geometry from nature (Chang et al., 2018a,b; 2019). The anchor has been tested in a centrifuge and in the Swan River (through a Woodside RiverLab project), confirming the diving ability and potential to achieve deeper embedment and greater capacity through diving upon loading (Figure 10).

Figure 10 Prototype trials of the 'fish' anchor in the Swan River, WA

5.4 SPUDCANS

Spudcan foundations provide support at the seabed for mobile independent-legged jack-up rigs used in offshore exploratory drilling, installation of new platforms and wind turbines, maintenance work and for hydrocarbon production for fields of limited life. The offshore industry is continually extending to new locations in unexplored environments with complex stratified seabed deposits. Challenges include the difficulty in obtaining high-quality soil samples for laboratory determination of soil properties, potential for catastrophic punch-through failure (costs $US5~50 million/incident), leg sliding or splay interacting with an existing footprint or crater, safer and quicker retrieval of spudcan and jack-up leg after the completion of tasks etc.

International guidelines such as ISO19905-1 have cited UWA work extensively, such as for estimating the spudcan penetration resistance in clay and the depth where backflow occurs (Hossain et al., 2005; Hossain and Randolph, 2009), and analytical approaches for punch-through resistance through a sand layer into clay (Lee et al., 2013). Macro-element models are considered the state-of-the-art for predicting foundation response under combined loading, with models for spudcan-soil interaction in sand (Bienen et al., 2006), soft clay (Zhang et al., 2012 a,b, 2013, 2014) and layered soils (Hu et al., 2017) included in ISO 19095-1.

For cost-effective and safe installation of jack-up rigs in problematic locations, the industry has identified the need to develop (i) software for estimating spudcan penetration resistance directly from in-situ cone penetration data, (ii) novel spudcan shapes for mitigating spudcan punch-through and spudcan-footprint interactions, (iii) innovative methods for retrieval for spudcans. These needs have driven industry-academia collaborations to address the issues by combining industry practical experience and academic research.

a) CPT-SP software: Keppel Offshore and Marine Pte Ltd: Keppel's concept was the integration of field penetrometer on-board jack-up rig, equipping every jack-up leg with an individual piezocone unit (Quah et al., 2008, 2010). This would allow immediate piezocone testing below or adjacent to the spudcan prior to jack-up preloading (Figure 11). Keppel completed the pertinent hardware development for the structural integration and approached COFS for the development of software through an ARC Linkage Project LP110100174. Software *CPT-SP* included two modules (Safinus et al., 2012, 2016). The first module allows real time identification of seabed layer boundaries and soil type for each layer directly from piezocone penetration profiles. The second module allows calculation of spudcan penetration resistance and identification of potential hazards such as punch-through. Keppel is incorporating the software in current generation jack-up rigs.

b) Novel spudcan shapes: Daewoo Shipbuilding and Marine Engineering Co. Ltd., Korea decided to enter the jack-up building market and approached COFS for support. They constructed a jack-up testing bed at Geoje city for the US$650 million Maersk project (Hossain et al., 2014). This was followed by the idea of developing new spudcan shapes for mitigating geotechnical hazards. ARC Linkage Project LP140100066 led to a skirted spudcan and a flat-based spudcan with holes through the base, as illustrated in Figure 12 (Hossain et al., 2015; Jun et al., 2020a, 2020b; Lee et al., 2020).

c) Leg retrieval: Leg extraction difficulties occur where spudcans are embedded by 2~3 diameters in clay and silt, with the leg removal process sometimes extending to several days or even months. Keppel approached COFS for optimising bottom water jetting or developing alternative solutions, leading to optimised jetting with a filling ratio of 0.7 (Gaudin et al., 2011). It was also shown that placing a sand layer between the base of the spudcan and the seabed surface (if not already present along the penetration path of the spudcan) may alleviate the leg retrieval issue, allowing base suction to be broken immediately upon extraction (Hossain et al., 2015).

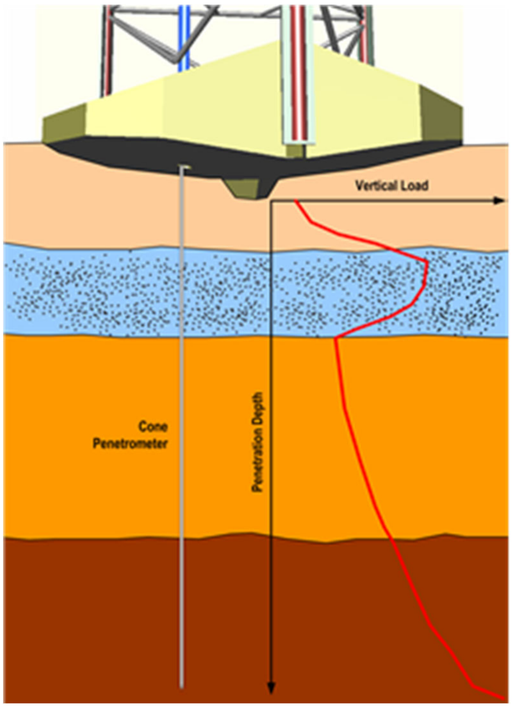


Figure 11 Penetrometer testing integrated with spudcan

(a) Skirted spudcan

(b) Spudcan with holes

Figure 12 New spudcan shapes for mitigating punch-through (a) and spudcan-footprint interactions (b)

6 EVOLUTION OF RESEARCH FOCUS AND MULTIDISCIPLINARY ASPECTS

COFS was established in response to challenging soil conditions and soil-structure interaction problems on Australia's North-West Shelf and has supported – directly or indirectly – all major offshore developments there as well as many others around the globe. With the energy transition globally to renewable sources, including wind, wave and tidal, COFS has broadened its focus and set its eyes firmly on new challenges. The diversified sources of funding (e.g. the LRF Chair and CoE) supported this shift before national competitive research funding allowed the portfolio of projects to grow. High impact resulted from collaborative research with partners in academia and industry (e.g. NGI, Fugro, TUHH, University of Oxford), with the majority to date relying on the unique capabilities that the NGCF offers. COFS is recognised as one of the leading research teams worldwide on foundations for offshore wind turbines, which is evidenced through invitations to deliver invited lectures (e.g. Bienen et al., 2019), incorporation of research output in industry guidelines and high impact in industry. Recent research already features in the first guideline for suction buckets supporting offshore wind turbines (Cathie et al. 2019) developed under the Carbon Trust, UK, which captures the current state-of-practice, while ongoing collaborative research with Lloyd's Register will be included in a new LR guideline that specifically addresses gaps in the state-of-knowledge through new research. Discussions in ISO committees on jack-ups have increasingly considered challenges facing jack-up wind installers. Active membership in these committees as well as continuous engagement with the industry network ensures that our research is relevant. The new context offers many interesting fundamental scientific challenges, and the multiple channels of communication and knowledge transfer ensure that our applied research addresses practical problems and provides prediction methods that are useful to engineering practice.As mentioned earlier, the InSafeJIP provided improved guidance for the installation and removal of oil and gas jack-ups. A new JIP, called J-REG (Jack-Up Renewable Energy Guidelines), has been convened under the auspices of SNAME to specifically provide guidance for jack-up wind installers. Interestingly, this brings together many of the individuals involved in the InSafeJIP (with companies including Vattenfall, Ørsted, EDF-Re, Equinor, BP, Shell, DEME Group, Gusto MSC, Van Oord and Jan De Nul), including three academics from COFS (Bienen), National University of Singapore (Okky Purwana) and the University of Oxford (Houlsby). The long-standing connections have built trust, and the symbiotic collaboration between industry and academia makes for high impact research outcomes.

The evolution of COFS research focus offers new exciting opportunities. Towards the end of the OFFshore Hub funding, attention turned to another emerging trend in the offshore industry, that of 'digital engineering', which is defined in this context as "*the creation, use and embedment of data in engineering*". This reflects a progressive transition in the offshore energy sector from large capital investment to long-term operation of assets and an associated need to lower to cost of future production to support an industry that is still essential to the national interest.

UWA prepared an ambitious bid, led by Phil Watson, for a second research hub – the Transforming energy Infrastructure through Digital Engineering (TIDE) Research Hub. This was awarded funding in 2020 and involves experts from the core engineering disciplines of oceanography, hydrodynamics, offshore structures and geotechnics, working collaboratively with experts from the fields of statistics, extreme value and decision-making theory, as well as machine learning. The project is an exemplar of collaborative research, evidenced by an expanded list of industry and research partners. The industry partners from the OFFshore Hub have been joined by a third operator (INPEX), with Fugro, RPS Group and Wood also joining as contractors/consultants tasked with translating research outcomes into practice through direct adoption. The Australian research team includes members from The University of Wollongong, The Australian Institute of Marine Science and The Bureau of Meteorology. International participants have been invited from the universities of Oxford, Lancaster, Southampton and Texas at Austin, as well as from the Alan Turing Institute, HR Wallingford and Technology Centre for Offshore and Marine.

Currently in the establishment stage, focusing on the development of projects prior to launching the project in mid 2021, TIDE will fuse data science techniques with engineering, leveraging industry acquired and experimental data, in order to transform the management of critical energy infrastructure (such as pipelines, structures and vessels) – making this process cheaper and yet more reliable. In so doing, it will assist Australian companies to cost-effectively maximise LNG export volumes, safely manage assets while minimising environmental risk, and train data science enabled engineers with exportable skills – ready to lead digital transformation of the energy sector.

Digitalisation is also taking place through the integration of design software developed by COFS into cloud computing for easier access and faster and more enduring update. Up until the 1990s, software was typically developed in the form of Fortran code which was compiled as a DLL and called from Excel™ (e.g. PIGLET: Randolph, 2003a; RATZ: Randolph 2003b). The more recent availability of low-cost on-demand cloud computing services motivated a move toward cloud-based software deployment with its many advantages. One advantage in particular is the ability to make software easily available globally. Another advantage of cloud-based applications is the ability to control access to a select group of users, and because application are run on a secure cloud environment, the intellectual property in the algorithm is much more secure than with desktop programs. Knowing their IP is secure gives businesses confidence to invest in developing new and innovative solutions.

As an example, UWA have worked with Fugro to build a proprietary cloud-based design platform. This consists of a number of foundation design tools (e.g. Doherty et al., 2018; Randolph et al., 2020). These applications required access to scalable computing power and were therefore built with multi-tiered architecture, involving a layer of user facing web servers and another layer of application servers that run the computationally intensive simulations (Figure 13). The two layers are connected via a queueing service. The number of application servers can be rapidly and automatically scaled up or down to suit the current demand. Therefore the system can run multiple simulations for many users simultaneously in a cost effective manner. The system has sped up calculation tasks, in some cases by several orders of magnitude. This enables design engineers to explore a range of options that may not have been possible previously and is another example of benefits of collaboration between university and industry.

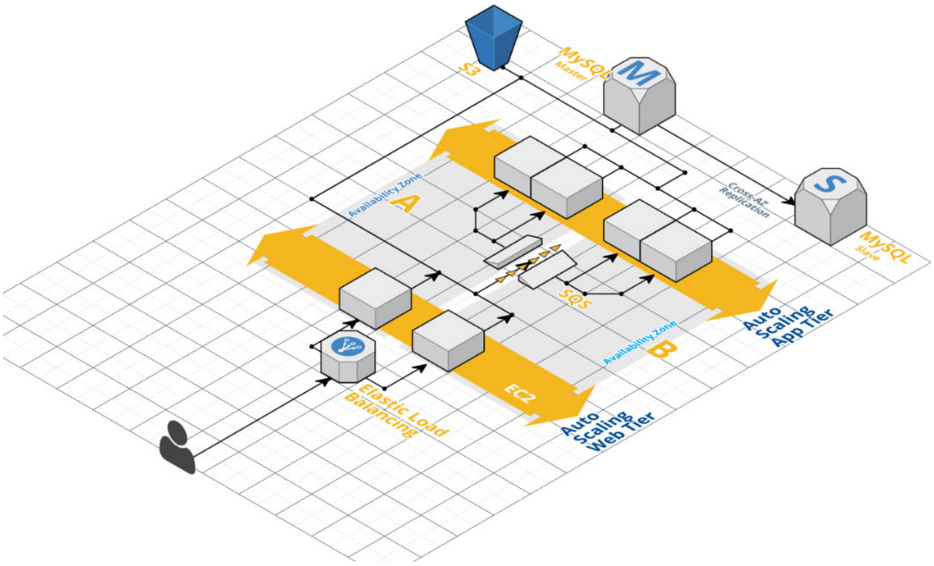


Figure 13 Cloud computing architecture

7 SUMMARY COMMENTS AND ACKNOWLEDGEMENTS

This paper has attempted to summarise collaborative activities at UWA in offshore geotechnical engineering, in terms of both the various mechanisms for linking with industry and also example technical outcomes that have had significant impact on practice. It has drawn on activities of the Centre for Offshore Foundation Systems (COFS) and the broader Oceans Graduate School, together with those from staff within the Department of Civil, Mining and Environmental Engineering. We are extremely grateful for the financial support from industry, which has averaged around $2 M annually over the last twenty years, and for continuous support from the Australian Research Council through its various programs. Support from other funding agencies including the State Government of WA is also acknowledged.

Authorship of the paper has been limited, for practical reasons, to current UWA staff, but grateful acknowledgement is made for the contributions of former staff. It is invidious to name but a few out of a very large number, but significant among these are: Martin Fahey, for many years Deputy Director of COFS; Mark Cassidy, Director of COFS during the oil and gas boom period; David White, inaugural Shell Chair in Offshore Engineering and leader of the ARC Offshore Hub; and other key researchers including Susan Gourvenec, Dong Wang, Yinghui Tian and Sam Stanier.

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The final category of acknowledgements is to the many staff in industry, including many former PhD students or staff members, with whom we have collaborated over the years, benefiting from the two-way transfer of ideas and knowledge. Our research impact would be reduced without these interactions and mention should be made of: Carl Erbrich, Technical Director of Advanced Geomechanics (AG) and now Fugro; Steve Neubecker and Ian Finnie, former Directors of AG; Michael O'Neill, who has recently rebounded from Fugro to rejoin UWA; George Zhang (AG now Fugro); Noel Boylan, formerly COFS, AG and now managing the Perth office of the Norwegian Geotechnical Institute (NGI); and Hongjie Zhou (now NGI) and Han Eng Low (Fugro), who made important contributions during their PhD research at COFS in establishing full-flow penetrometers.

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