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Geotechnical centrifuge modelling and the energy transition – 'same old same old' or are there more foundation challenges on the horizon?

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ABSTRACT: Geotechnical centrifuge modelling has (for decades) aided our understanding of real-world foundation behaviour. When used in combination with numerical/analytical analysis, the outcome is robust design practice. With world attention on the pursuit of renewable energy, including offshore wind, this paper explores the differentiators to oil and gas geotechnical engineering, outlines a framework to measure technology readiness, and argues that centrifuge modelling plays a key role in advancing individual technologies towards eventual deployment – as demonstrated through case studies at different stages of development.

1 Introduction

The use of geotechnical centrifuge modelling to improve our understanding of real-world foundation behaviour and to complement design is not new. Indeed, the most recent McClelland Lecture (Clukey, 2020) provides a number of excellent case studies of exactly this – ranging from foundation capacity to soil-structure interaction problems. With world attention on renewable energy – including for offshore applications – this paper builds on those earlier efforts by focusing on the role of physical modelling to aid the energy transition. High level review of 'new' challenges linked to offshore renewables (and specifically offshore wind) is followed by the introduction of a technology measurement system – against which the role of centrifuge modelling can be assessed, and through which it is shown that physical modelling plays a key role in aiding engineers to screen potential technologies, and then progress those selected for use towards deployment. Three case studies – representing technologies at differing levels of development – are then presented to support the discussion.

Before progressing further, two brief caveats require mention:

1. The research outcomes presented in this paper are (unashamedly) empirical in nature – first presenting the problem being solved, and then describing the results from testing aimed at addressing this problem. In reality, solutions to these problems will not come from centrifuge modelling alone – but typically require a combination of both physical modelling and analytical/numerical analysis, complemented by well-defined soil parameters, to achieve the best outcome.
2. While focused on centrifuge modelling, similar arguments could be made for the importance of other forms of physical modelling – such as laboratory floor and field testing. These have equally important roles supporting the energy transition. While outside the scope of this paper, examples are provided elsewhere in this conference.

2 Centrifuge modelling for the energy transition

2.1 *Introducing the National Geotechnical Centrifuge Facility (NGCF)*

Centrifuge modelling has supported geotechnical engineers and researchers for many decades. Outlined in Gaudin et al. (2010), the centrifuge is a tool to *(i) validate concept and designs, (ii) observe the response of geo-structures under specific loading regimes, and (iii) gather performance data to calibrate numerical models*. This is true regardless of what part of the offshore sector a problem originates from.

There are a large number of centrifuge facilities around the world – many of which perform testing for both commercial and research purposes. The case studies presented in this paper involved testing at the National Geotechnical Centrifuge Facility (NGCF) at The University of Western Australia (UWA). The NGCF operates three individual centrifuges – two beam centrifuges (Figure 1) and one drum centrifuge – with the beam centrifuges used for the case studies presented in this paper.

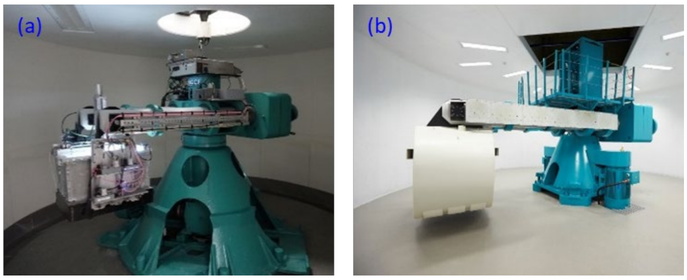

Figure 1. Beam centrifuge facilities at the NGCF (a) 3.6 m diameter / 40 g-tonne; (b) 10 m diameter / 240 g-tonne

2.2 *What's different about offshore wind?*

Geotechnical engineers have supported the oil and gas sector since its early days, addressing challenges in fixed and floating infrastructure and more recently, for subsea developments. So, from a geotechnical perspective – what's new about offshore wind (used in this paper to reflect the energy transition)? Illustrated in Figure 2, the authors contend there are four key differentiators:

1. Wind is being developed in new offshore regions, where there has (historically) been limited (or no) offshore development and where local design experience may not exist. In addition, many wind farm locations have shallow water depth (relative to recent oil and gas developments) – which typically leads to more varied seabed conditions.
2. Relative to oil and gas developments, wind farms have large spatial extent and high numbers of individual structures.
3. Structures supporting wind turbines are more slender (and therefore more dynamic) than most oil and gas structures, with low self-weight and (reflecting the height needed to access reliable wind and provide clearance for the turbine blades) high overturning moment. Adding to this, sensitivity of the turbines leads to tight displacement constraints.
4. While cost is always a driver on offshore developments, this is amplified for offshore wind due to tight project margins.

These differentiators overlap – creating the conditions for significant challenges to arise, which need to be overcome by offshore geotechnical engineers.

So what are the geotechnical challenges? Figure 3 summarises several of them, overlaid against the differentiators outlined above – but noting that this is not an exhaustive list!

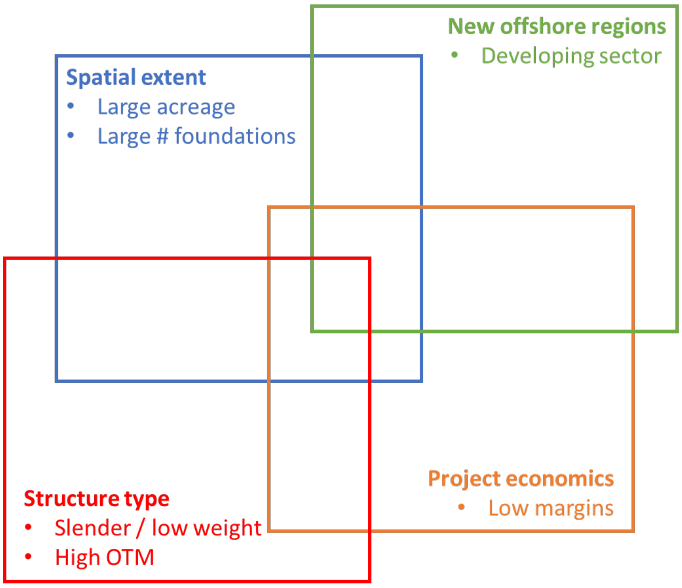

Figure 2. Offshore wind 'differentiators'

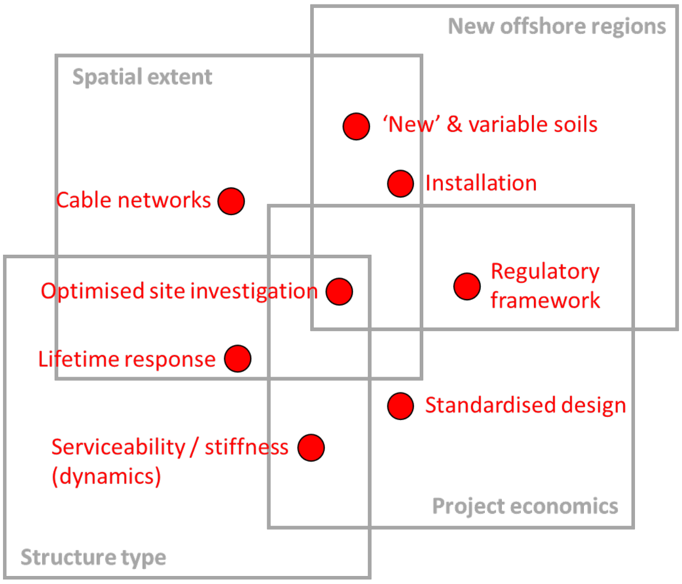

Figure 3. The geotechnical challenges

Some of the challenges reflect regional considerations – such as encountering new soils; or working in areas where existing regulations need to be adapted for offshore wind projects. Linked to this may be challenges associated with installation of wind farm foundations – for example, in environmentally sensitive areas, or where ground conditions are unproven.

The spatial extent of offshore wind projects leads to challenges managing an array of subsea power cables, while project economics motivate efficient site investigation and design optimisation – the latter unlocking savings during fabrication / construction.

Finally, unlike for conventional oil and gas projects where foundation design tends to focus on stability first and displacement second – the opposite is true for wind. Tight rotational tolerance over the life of a turbine means it is critical to reliably predict long-term response; while foundation stiffness can impact the efficiency of the turbine itself – possibly influencing project economics.

Overall – it is clear that the energy transition will produce challenges for geotechnical engineers for decades to come.

2.3 *Can geotechnical centrifuge modelling help?*

Geotechnical centrifuge modelling is a tool that can assist in tackling the above challenges by:

- Validating concepts & supporting new technologies as they mature;
- Exploring parameter sensitivity & optimising design outcomes;
- Demonstrating response in site specific seabed conditions; and
- Informing reliability studies and understanding risk.

Centrifuge modelling is cost effective, fast and data rich – and when used in combination with numerical/analytical tools – can facilitate the generation of robust, tailored project outcomes.

2.4 *Technology Readiness Level*

It is evident that the expansion of renewable energy in the offshore environment will create new challenges, and that centrifuge modelling has a role to play in addressing these – but can we quantify this?

To do so, we can leverage the 'Technology Readiness Level' (TRL) concept, which was first developed by NASA in the 1970s. Designed as "*a type of measurement system used to assess the maturity level of a particular technology*" (NASA, 2012), this system provides a common framework to assess the readiness of an engineering technology for deployment regardless of the field it comes from – while also providing clear 'exit gates' to progress the technology towards deployment. Originally developed with nine levels, the TRL concept has been adapted by many organisations since it was first introduced. For the purposes of this paper, the authors propose grouping the levels as shown in Figure 4.

The first (lowest) grouping relates to solutions at the 'proof of concept' level and equates (broadly) to TRL 1-3. This covers initial ideation and framing, through to initial laboratory (including centrifuge) experiments used to investigate key principles and limitations. Passing this stage implies that the proposed technology is worthy of further study.

The second grouping is of particular significance to centrifuge testing, as it highlights one of the key advantages of modelling – that being the ability to perform high quality parametric studies that can be used to frame a new technology. Designated 'define / validate' and equating to TRL 4-5, this stage involves parametric studies and model validation – and is often used in parallel with numerical or analytical studies. At the end of this stage, the engineer should have a clear understanding of the factors influencing the performance of the particular technology being considered.

For technologies that are well understood, the 'design' stage (TRL 6-7) involves studies that support their adoption on projects. In this case, experiments can be used to compare (rank) different technologies, and to identify risks associated with their deployment. Centrifuge modelling may also be used to support detailed engineering of individual concepts, involving highly detailed modelling of concepts subject to project specific load/deformation scenarios and seabed types, and with results used to support project decisions.

The final (highest) grouping is characterised in this paper as the 'forensic' stage and equates to TRL 8-9. To be included in this grouping, the technology should already be in use, in which case centrifuge modelling can be employed (for example) to optimise its performance in order to produce a better project outcome – such as through increased efficiency, improved safety or better project economics. Centrifuge modelling can also be used when unforeseen problems are encountered during deployment, in which case small scale modelling may provide a cost-effective means of studying potential cause(s) and identifying mitigation measures.

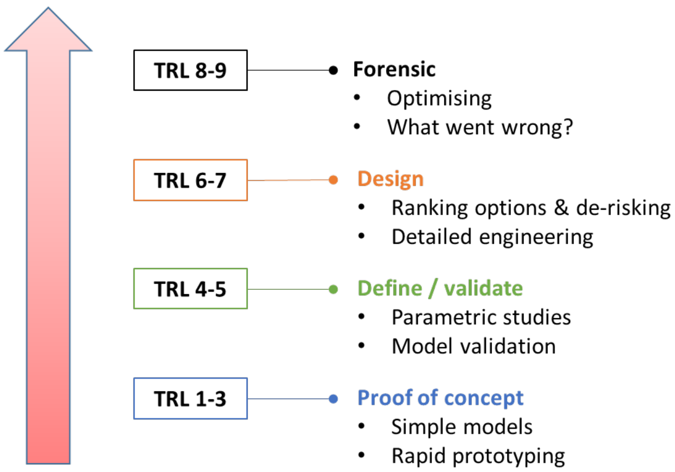

Figure 4. Adapting the 'Technology Readiness Level (TRL)' concept for centrifuge modelling

While individual groupings are open for debate, the authors contend that centrifuge modelling is a viable, cost-effective tool to support the progression of individual technologies from concept stage through to full deployment, as well as for continued design optimisation.

Accordingly, the following sections provide case studies (at different TRL levels) where centrifuge modelling has been used to advance a proposed technology. In each case the technology in question relates to offshore wind energy, with the testing used to advance the concept towards a higher TRL.

3 Low TRL example: Suction (flow) assisted driving of monopiles

3.1 *Introducing the concept*

The first case study relates to the installation of offshore monopiles and explores a TRL proof of concept to reduce noise in the marine environment.

Monopiles have emerged as the preferred foundation to support offshore wind turbines in water depths up to around 60 m. With diameters up to 10 m (or more) they are typically installed using pile driving – the noise from which can be harmful for marine mammals; which is a key environmental consideration in many emerging offshore wind regions (including Australia). Mitigating this noise can be achieved through the use of 'bubble curtains', which adds time (cost) and complexity to offshore operations. Alternatively, vibropiling is being widely studied as a potential low noise alternative (e.g. Hein Mazutti et al, 2023). However, is there a way to reduce the amount of marine noise from pile driving by (significantly) reducing the number of blows to install a monopile? That is the concept being explored here.

Suitable for sand sites, this simple idea combines two known technologies:

1. *The installation of suction caissons in sand.* It is well understood that lowering the water pressure within the caisson will lead to seepage in the seabed (Byrne & Houlsby, 2002), which reduces the effective stress at skirt tip level. If adapted to the case of a monopile installed in sand, the change in effective stress has the potential to reduce the resistance to driving and thus lower the blow count.
2. *The use of pumps to lower water level in jacket legs to aid installation.* Installation of the Yolla A WHP (Watson & Humpheson, 2007) involved the use of large volume pumps to lower the water level in jacket chords (legs) – demonstrating the practicality of moving large volume of water in time frames suited to offshore installation.

The concept is illustrated in Figure 5. Note that it is proposed only to lower the water level inside the monopile – not to create an environment in which suction adds to the installation force.

3.2 *Centrifuge testing*

In order to explore the viability of this concept, a centrifuge testing program was undertaken in the C72 beam centrifuge at UWA. The tests involved installation of a 50 mm diameter model monopile at 80 g (4 m prototype) into a medium dense silica sand saturated with pore fluid of viscosity around 100 cSt. A tube was used to lower the water level within the monopile, with testing undertaken to explore the effect of increasing head drop and varying the duration over which this was applied. The model is illustrated in Figure 6, which also suggests this concept has a TRL consistent with the 'proof of concept' stage.

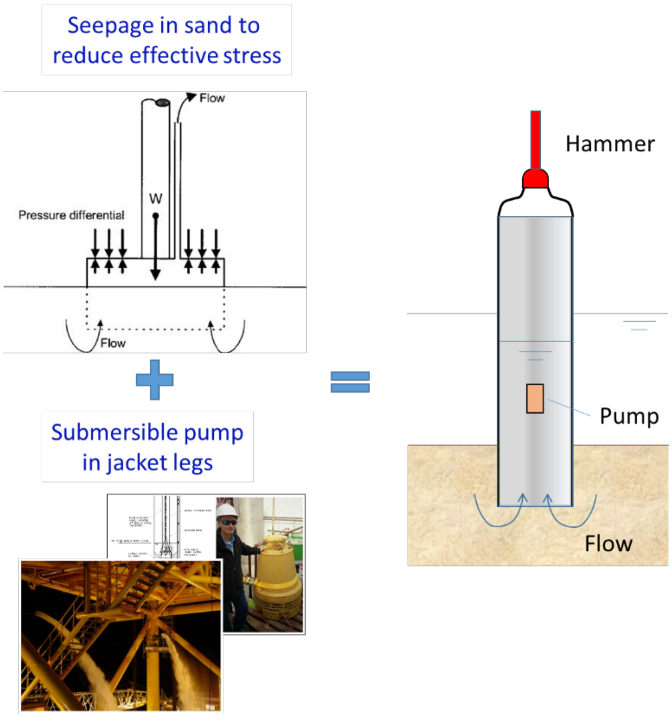

Figure 5. Can flow be used to reduce driving resistance?

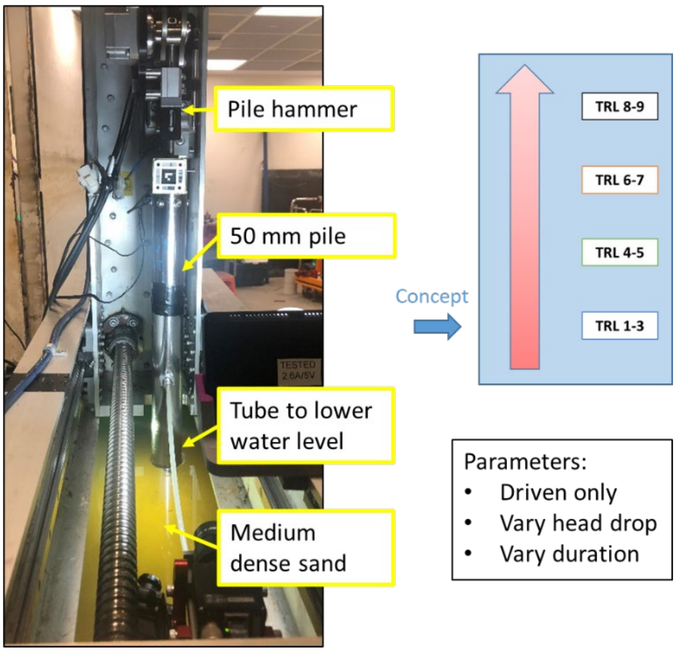

Figure 6. Setup used to vary head drop during driving

In keeping with the (low) level of maturity of this concept, the testing made use of existing models as much as possible – which meant that only a limited range in head drop could be explored. While considered suitable for prototyping, further development of this concept (at higher TRLs) would require the development of a bespoke model.

Each test involved self-weight installation of the monopile to around 50 mm tip penetration (equivalent to 4 m at field scale), followed by driving in flight to the target final embedment.

Figure 7 summarises the results obtained for three test cases, whereby:

- Figure 7(a) shows the variation in total blows with depth over 100 mm (8 m prototype) from the start of driving; and
- Figure 7(b) shows the reduction in blows relative to monopiles driven to full depth.

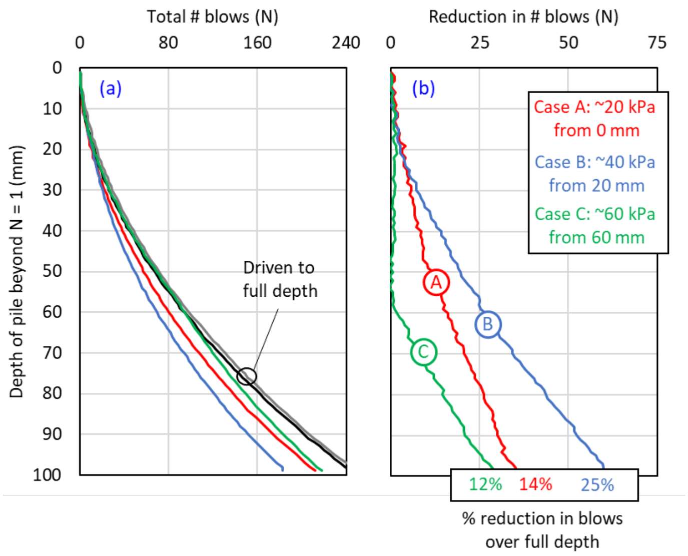

Figure 7. Impact of flow on observed number of blows

The three 'flow' cases explored were:

1. Case A involved a 20 kPa (2 m prototype) reduction in water level within the monopile, which was applied at the start of driving and maintained to full depth. The results show a progressive reduction in blow count, equating to ~14% fewer blows over the full profile.
2. Case B involved a higher (40 kPa) reduction in water level, which was applied after 20 mm of monopile driving and maintained to full depth. The first 20 mm of driving is consistent with the driven-only case, with the blow count reducing only after lowering of the water level. The overall result was a blow count reduction of ~25%.
3. Case C involved an even higher (60 kPa) reduction in water level, which was applied roughly halfway through the driving phase. As for Case B, the driven-only stage was consistent with tests that excluded the head drop – with a clear reduction in blows evident as soon as the water level was reduced. While the reduction in blow count was less for Case C (only ~12%) this likely reflects the limited time over which the reduced water level was applied.

Overall, the results are promising and show that reducing the water level inside a monopile can lead to a reduction in blow count. As would be expected, the overall 'benefit' is a function of both the level of water level drop and the duration over which is it applied.

A 'like for like' comparison is provided in Figure 8, which looks at driving over the final 10 mm only – and which plots the blow count reduction against water level reduction normalised by the effective stress at pile tip level (using $\gamma' = 10$ kN/m^3). The following observations are made:

1. The reduction in blow count is significant given the modest water level reduction relative to the effective stress at pile tip level (noting that the reduction in effective stress will be lower than the water level reduction).
2. Case B and Case C show a similar blow count reduction, despite the higher water level drop for Case C. This could reflect the longer duration over which the pressure drop was applied in Case B (giving more time to establish flow in the sand).

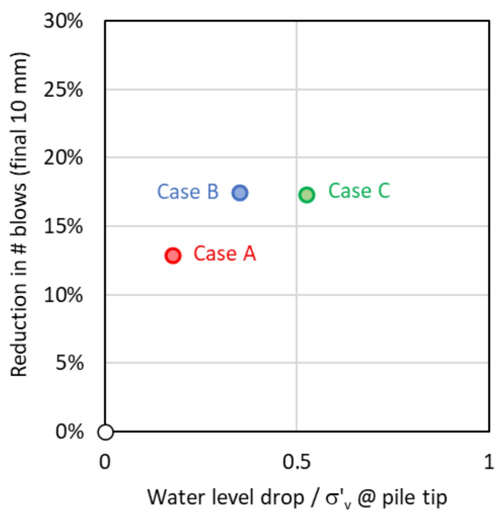

Figure 8. Reduction over final 0.2D of driving

A final aspect investigated in this study was the behaviour of the soil plug during driving. This was explored by positioning pore pressure sensors on the sand surface inside the pile and on the pile itself, with the results then interpreted in terms of a change in plug level. The results shows that the pile cored to full depth, with no significant change in seabed elevation inside the pile.

3.3 *Outcome*

This first case study explored the use of centrifuge modelling at the 'proof of concept' stage. Testing made use of (largely) available apparatus, which provided a limited range of variables that could be tested. Despite this, the potential to reduce the number of driving blows to install a monopile in sand is clear, suggesting this concept is worthy of further study – which may represent a means of significantly reducing marine noise. Additional testing would need to explore the parameters governing this behaviour, and how they can be controlled to increase reliability.

At this stage, and given the relatively limited scope of testing, there is insufficient evidence to argue an increase in TRL beyond the 'concept' stage – and further work is recommended. In parallel with this, practical considerations associated with adopting this concept in the field need to be addressed.

4 Intermediate TRL example: Plate anchor installation in sand

4.1 *Introducing the concept*

The second case study relates to mooring of floating wind turbines with plate anchors. This is considered at the 'validate' stage, with testing undertaken to assess the potential of plate anchors to reduce project cost in a wide range of seabed types.

Plate anchors generate their holding capacity through bearing against the surrounding soil. They can be installed using a retrievable suction caisson – specifically via the Suction Embedded PLate Anchor (SEPLA) technology (Wilde et al. 2001), as highlighted in Figure 9. This concept is well understood in fine grained soils and has been used for both temporary and permanent moorings in the oil and gas industry – and so has a high TRL. However, many floating wind projects are proposed in water depths where the seabed may comprise interbedded and/or coarser sediments – and in this case, the use of SEPLAs is not proven. Nonetheless, the large number of anchors needed to support floating offshore wind installations necessitates the importance of finding a cost-effective solution.

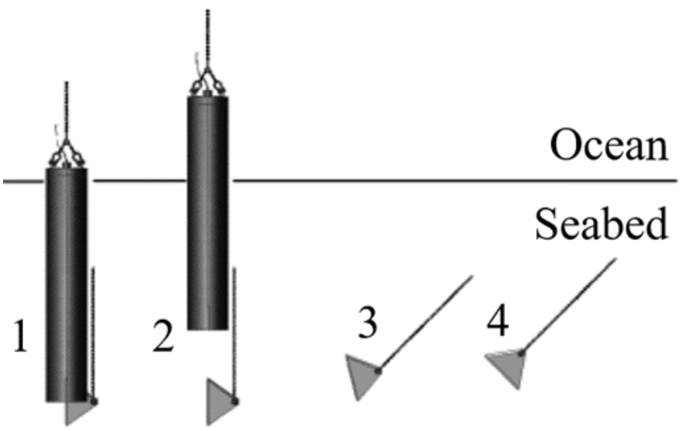

Figure 9. The SEPLA concept (after Gaudin et al., 2010)

Preliminary testing in O'Neill et al. (2023) has shown that installation in sand is feasible and the installation process does not appear to impact anchor capacity. However, this testing involved the use of a self-weight (to achieve initial embedment) that is higher than would likely be available offshore. Accordingly, the following questions need addressing to increase confidence in this concept:

- Can we install with a realistic self-weight?
- Are there any installation limitations?

4.2 *Centrifuge testing*

The modelling outlined below builds on the results in O'Neill et al. (2023), but with a number of parameter modifications:

1. A similar model set up was adopted, with testing performed at 100g in the C61 beam centrifuge at UWA. However, the caisson was modified to explore the option of retracting the plate anchor inside the caisson – which is expected to increase installability.
2. While the same (medium dense) silica sand was used for the new tests, the viscosity of the pore fluid was increased by a factor of 5 (to 500 cs) in order to better explore risks associated with seepage through the sand – which has implications for the pumping rate.
3. After extraction of the caisson, all plate anchors were loaded vertically to failure. To improve our understanding of the anchor load-displacement response, additional (standalone) tests were performed with an accelerometer attached to the anchor, which allowed for observation of when the anchor started to rotate relative to the anchor line tension.

Figure 10 shows the model caisson and two anchor positions considered in this study, as well as the proposed TRL for the concept.

An initial set of tests explored the potential to reduce self-weight for the case of the protruding anchor. Results are compared to a caisson-only (no anchor) case and shown in Figure 11, whereby:

- Figure 11(a) shows the vertical load applied to the soil. In all cases, the caisson is pushed to a pre-determined vertical load (representing the self-weight), which is then held constant through the suction phase. Test C is the caisson-only test, which was installed to a tip embedment of around 10 mm assuming 200 N (model scale) self-weight. The first of the SEPLA tests (Test 1) was also installed to 10 mm but required roughly 1 order of magnitude higher self-weight to achieve this embedment. The subsequent SEPLA tests (Test 2 and Test 3) explored the effect of reducing self-weight, targeting 7 and 5 times the caisson-only value respectively – noting this came at the cost of reduced initial embedment.

- Figure 11(b) shows the (measured) suction required to advance the caisson at the applied self-weight – and as can be seen, higher suction was needed to compensate for lower self-weight. Although not shown, additional SEPLA tests were attempted at even lower self-weights – but it was not possible to achieve a seal at the associated (minimal) skirt tip embedment, meaning the caisson could not be advanced through suction.

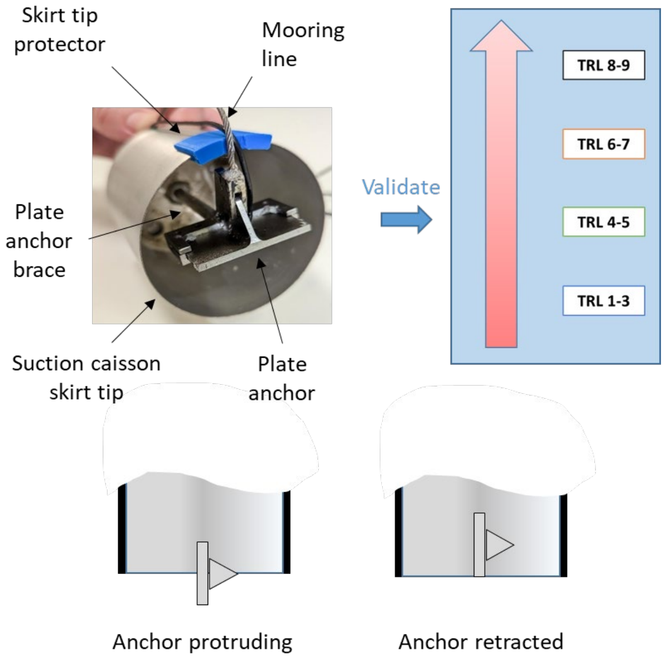

Figure 10. Location of plate anchor relative to skirt tip

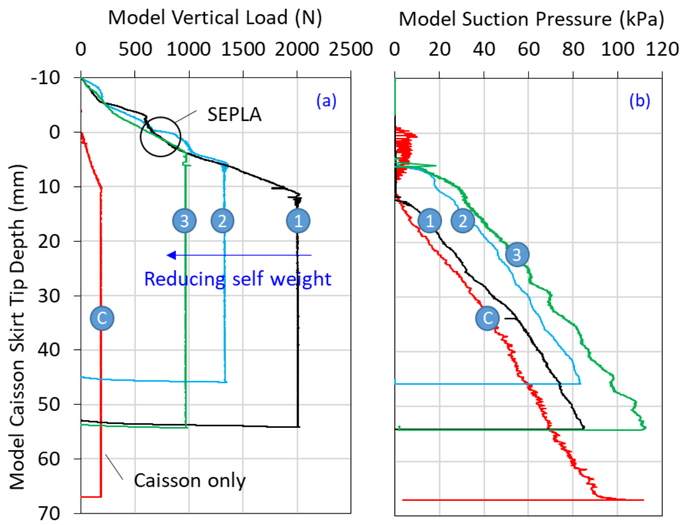

Figure 11. Effect of reducing self-weight on observed suction pressure – anchor in protruding position

The testing above is further presented in Figure 12, in which the total (model) penetration resistance is shown – this being the combination of self-weight and suction pressure. It is clear that the higher suction pressure (associated with lower self-weight) leads to a net reduction in installation resistance – as seepage through the sand leads to greater reduction in effective stress at tip level (at higher suction).

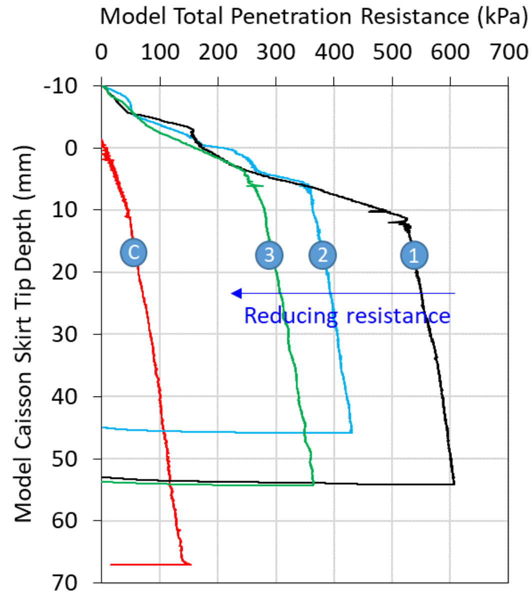

Figure 12. Total resistance – anchor in protruded position

While the initial testing suggests that installation is possible at lower vertical load, the required self-weight for the protruding anchor case remains significantly above the weight of the caisson only case. Accordingly, the next stage of testing involved retracting the anchor inside the caisson – such that the lowest point on the anchor was at skirt tip level. Results from testing are shown in Figure 13, whereby the self-weight was progressively reduced from 2.5 to 1.25 times the self-weight of the caisson-only case.

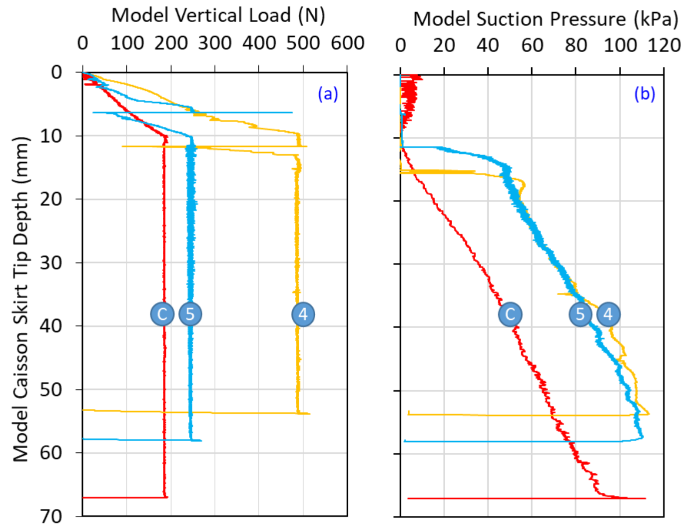

Figure 13. Retracting anchor (to skirt tip) enables installation at reduced self-weight load

Of particular interest is the observation that the suction pressure for both SEPLA cases is the same –

apparently in contrast with that seen for the protruding anchor case. Figure 14 compares the suction pressure observed in these two (anchor retracted) cases with that observed in Test 3 (with the lowest self-weight) from the protruding anchor test series. All three cases track a consistent relationship between suction pressure and caisson skirt tip depth. This 'limiting suction' is roughly equal to twice the effective stress at skirt tip level (using $\gamma' = 10\ kN/m^3$) and appears to represent an upper limit on design suction at the respective depths.

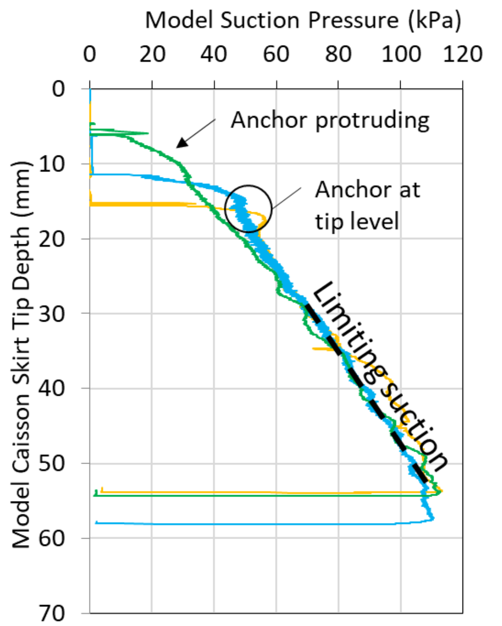

Figure 14. Limiting suction pressure

The final aspect of installability explored in this study was to examine the effect of pumping rate. This addresses a concern that if the pumping rate is too slow and offset by the volume of seepage through the sand, then the caisson may cease to advance. To explore this, SEPLA tests were performed where the model pumping rate was varied, with detailed results as shown in Figure 15.

Three tests are reported, all performed with the same self-weight (500 N at model scale):

- A baseline test (in blue) was performed first, using a constant pump rate equivalent to around 800 mm^3/s (model scale). The data show that as suction pressure increased with embedment, the advancement ratio (representing the embedded caisson internal volume versus the volume of water removed from the caisson) reduced from an initial value of around 0.8 to around 0.3 at the maximum depth achieved.
- The first variation test (in red) involved reducing the initial pump rate by nearly two orders of magnitude. While suction could be generated, the advancement ratio was very low – and the caisson stopped embedding entirely after a short distance. The pump rate was then increased to that of the baseline test, with the remainder of the test showing a consistent result.
- The second variation test (in green) went even further, exploring installation at a range of pump rates. The first stage was performed at a pump rate roughly five times lower than the baseline test – the observed suction pressure was between that of the first variation test and the baseline test, with the advancement rate progressively slowing until the caisson stopped embedding. The pump rate was then increased to be roughly 2.5 times lower than the baseline test – the observed suction was slightly higher than that seen at the lower pump rate (but lower than the baseline) and the caisson again stopped penetrating after a short distance. The pump rate was then increased to that of the baseline test, with both suction pressure and advancement ratio increasing accordingly.

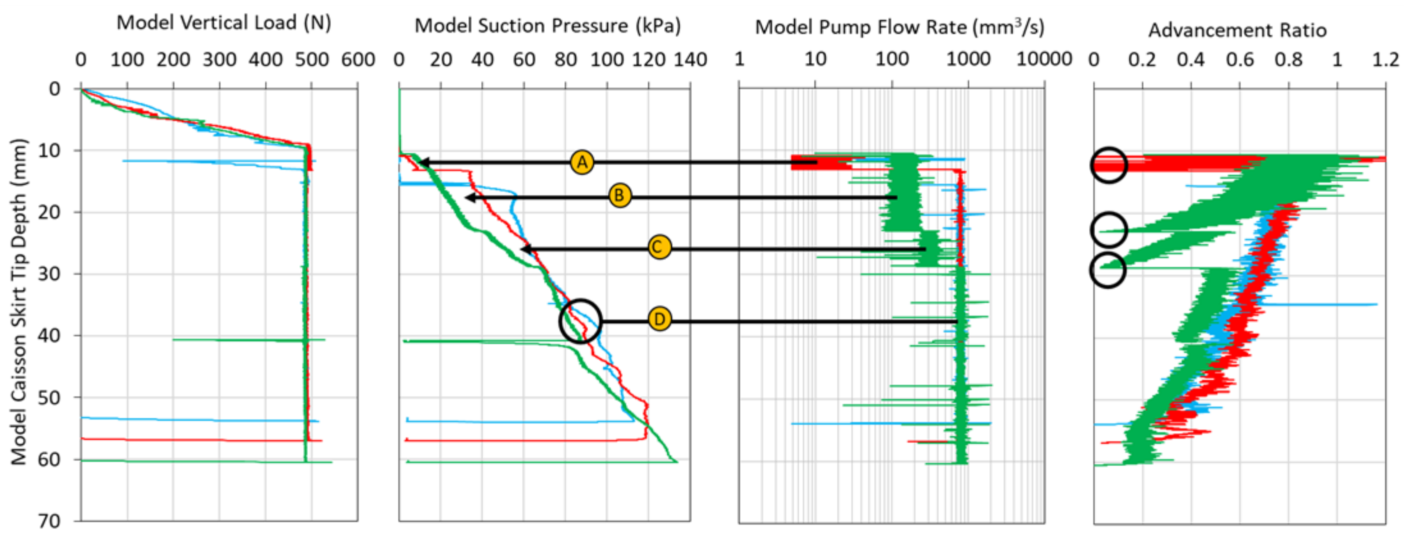

Figure 15. Effect of pumping (penetration) rate on installation

This insightful set of model tests show that while reducing the pump rate can lead to lower suction pressure being required to install the caisson – presumably due to establishment of flow in the sand – there is the risk that significantly reduced advancement ratio (and even complete stall) of the caisson will occur. The results appear highly sensitive, with relatively modest changes in pumping rate leading to significant change in response – highlighting the importance of understanding this balance when installing SEPLAs in sand.

The final elements of this study relate to (a) improved understanding of the anchor load-displacement response of the anchor; and (b) investigating the anchor ultimate holding capacity.

In order to investigate the load-displacement response, a series of tests were performed in which the plate anchor was pushed (jacked) into the sand without use of the caisson. This allowed an accelerometer to be attached to the anchor, which could then be interrogated as a means of understanding the anchor rotation when loaded. Results from two tests are presented below – in Figure 16(a) the padeye attached to the plate (and the anchor line itself) is vertical; while in Figure 16(b) the padeye was kept horizontal during installation. The latter is considered representative of a SEPLA, whereby the anchor chain needs to pass under the skirt tip – thereby introducing some 'slack' that must be taken up prior to the anchor starting to move. Important observations can be made from these tests, as follows:

- When the padeye is vertical, the anchor begins to rotate at the same time as the tension load increases. In contrast, the horizontal padeye case shows a large increase in applied tension without the anchor moving – which is attributed to the chain 'cutting' through the sand. By the time the anchor starts to move, nearly 40% of the peak tension has been mobilised.
- Both tests demonstrate an interim phase where the anchor rotates without any large increase in line tension – although this is most evident for the vertical padeye case. This is thought to coincide with a phase during which the anchor is primarily undergoing rotation with limited (upwards) translation – and beyond this the anchor movement is primarily translation.
- Both tests have comparable peak tension, which is reached at around 20 mm (one anchor diameter) vertical line movement after the anchor starts rotating – giving an indication of the reduction in anchor embedment. Additionally, for both cases the peak tension is reached (just) prior to the anchor rotating into a fully horizontal position.

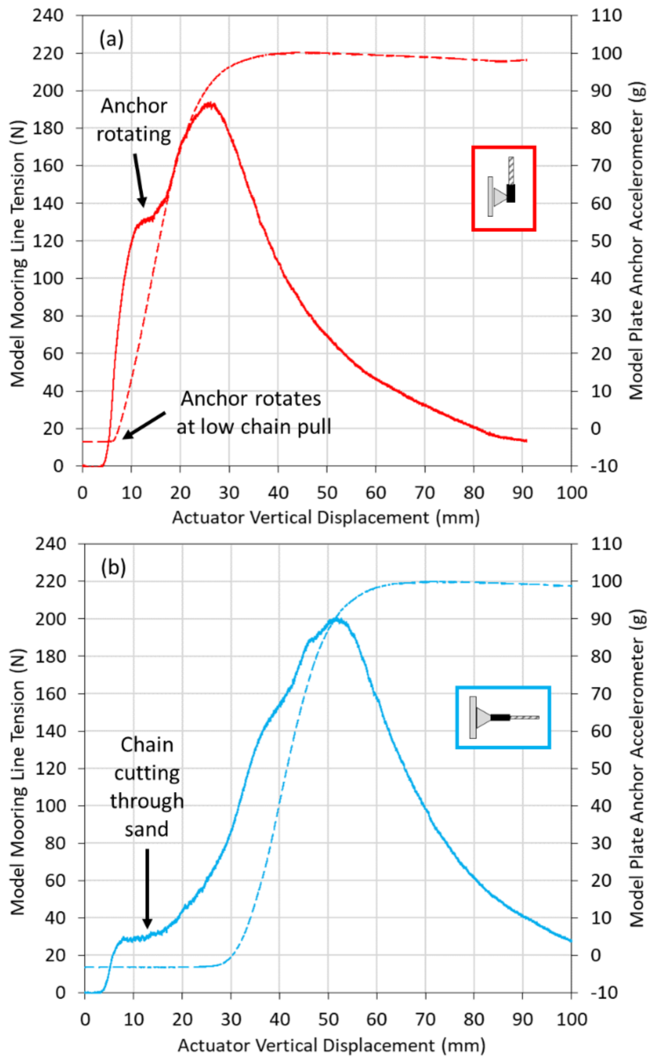

Figure 16. Load-displacement response, with anchor rotation

Overall, these results shed light on plate anchor kinematics in sand and can be used to support the development of analytical models.

Finally, the plate anchor ultimate holding capacity observed in all tests is normalised in Figure 17, including data from O'Neill et al. (2023) and the tests presented in this paper. Note that in all anchor pullouts the extraction rate was set such that a predominantly drained response was obtained. The results are divided based on whether the anchor was installed with suction (SEPLA) or pushed to depth – no clear difference is observed, suggesting that suction installation does not adversely impact anchor capacity.

Of interest, one test showed lower resistance than the others – on removing the anchor it was noted that the connecting wire had been crimped, and that the plate anchor was not acting perpendicular to the load direction – highlighting the importance of ensuring (in practice) that the plate anchor remains free to rotate into an optimum position.

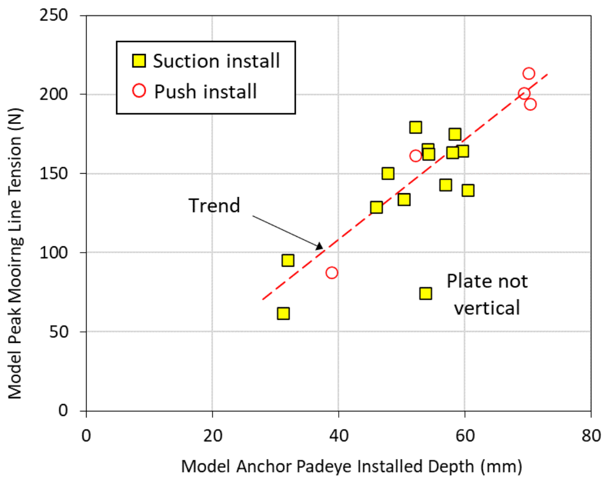

Figure 17. Anchor pullout capacity

4.3 *Outcome*

This second case study explored the use of SEPLA technology in sand, as a step towards validating its use in support of floating offshore wind.

The tests reconfirm that installation in sand is possible, and that this can be achieved at a realistic self-weight once the anchor is retracted inside the caisson. The importance of pump rate was also investigated – highlighting the delicate balance between pumping slow enough to reduce penetration resistance, but not so slow as to cause penetration to stop. Testing provided data on anchor kinematics in sand and suggests that anchor holding capacity is not affected by the installation process.

Overall, centrifuge modelling provides strong evidence supporting the use of SEPLAs in sand. However, more data is needed in a range of seabed conditions – supported by analytical/numerical studies. It can be argued that the insights provided through this preliminary set of tests has helped push the TRL to the upper end of 'define / validate' – and with more testing now planned in order to take this technology into 'design'.

5 High TRL example: Performance of suction buckets in sand subject to prolonged uplift

5.1 *Introducing the concept*

The final case study addresses the performance of suction buckets in sand when subject to combinations of cyclic load and long-term (average) uplift. This is considered to be at the 'design' stage, given the maturity of suction buckets as offshore foundations – with the centrifuge tests performed as a means to maximise their performance.

As background, suction bucket jackets have been used successfully to support offshore wind turbines, including in sand seabeds (Shonberg et al., 2017), and are becoming more popular as water depth increases – an example being the installation of suction bucket jackets for the Seagreen Ofshore Wind Farm, which includes the deepest such installation to date (Seagreen Wind Energy, 2023). They are considered to be at high TRL and leverage technical advancement from the oil and gas sector. However, concern remains over their performance in sand when cycling at close to zero average load – for instance, the "Suction installed caisson foundations for offshore wind: design guidelines" (Offshore Wind Accelerator, 2019) states that "*significant caution should be exercised in designing a SICF [suction installed caisson foundation] for cycling out of compression and into tension for anything other than the ULS condition*". This recommendation appears to stem primarily from adverse findings of past testing campaigns – can we improve on this, and push their use in a wider range of design cases?

Recent studies have considered cyclic loading scenarios with average loads close to zero, as presented in Low et al. (2023). That paper concluded there were limitations associated with past test campaigns – which were undertaken either at 1 g or in centrifuge models with low simulated water depth, or in which unrealistic drainage conditions were modelled – and used new testing to show that suction buckets can (in certain scenarios) be cyclically loaded at close to zero average load without large displacement. Results from the study presented below go even further, exploring the performance of suction buckets when cycled around long-term average uplift load.

5.2 *Centrifuge testing*

Consistent with Low et al. (2023), the testing presented in this paper only considers the performance of the trailing (windward) bucket in a jacket configuration (Figure 18). Tests were performed at 150 g using a model bucket with diameter 80 mm and length 80 mm (equivalent to 12 m × 12 m at field scale). In all tests the bucket was installed using suction, before being subject to 'pre-shearing' (low amplitude vertical cycling) to represent historical loading on the foundation. After pre-shearing, the test conditions were applied.

The soil profile being modelled was dense sand. In order to correctly scale the generation and dissipation of pore pressure, it was decided in this case to use a sandy silt with water as the pore fluid – taking advantage of the lower permeability, instead of introducing a high viscosity pore fluid. The sandy silt was mineralogically similar to that of the sand being modelled but included a fine fraction – with laboratory (element) testing performed to verify that the compressibility and monotonic/cyclic shear strength characteristics were similar to that of the target sand. Sample preparation was broadly consistent with that outlined in Mani et al. (2023).

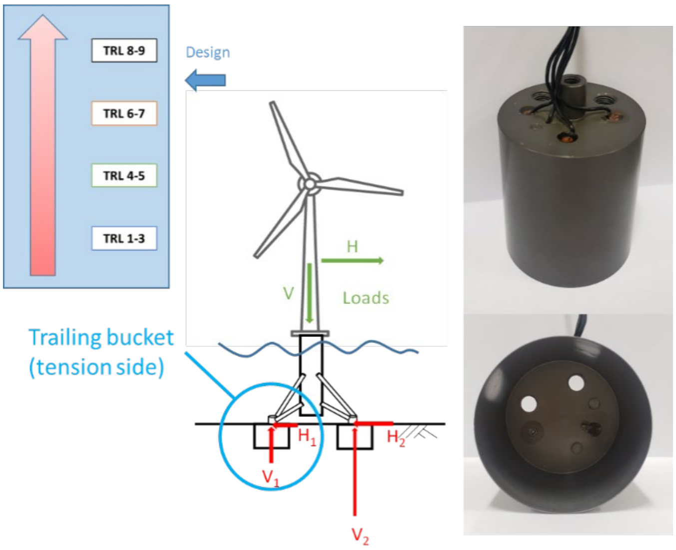

Figure 18. Uplift loading of bucket foundations (jacket configuration for illustration purposes only, after Low et al., 2023)

As discussed in Low et al. (2023), the response of suction buckets at close to zero average load is highly dependent on the drained tension capacity (R_d). Figure 19 shows the results of a (slow) drained uplift test undertaken for the present study, with peak capacity (vertical load divided by bucket cross-sectional area) of $R_d \sim 70$ kPa reached at a vertical displacement of around 0.2% of the skirt length.

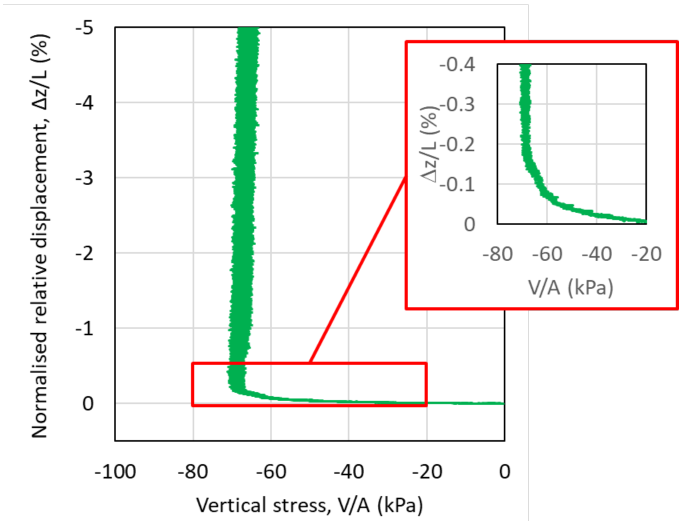

Figure 19. Drained tension capacity

Informed by the drained resistance, three cyclic tests were planned, as described further below:

- CYC1 was performed with modest average tension (~25% of R_d) and high cyclic tension (~70% of R_d) – and with over 10^5 cycles applied.
- CYC2 was performed with high average tension (~60% of R_d) and modest cyclic tension (~25% of R_d) – and with nearly 10^5 cycles applied.
- CYC3 involved progressively increasing the applied average and cyclic loads (in packets of 10^3 cycles) until the onset of continuous cyclic uplift displacements was observed – which occurred in the third packet (CYC3-3).

The applied load cases are illustrated in Figure 20. All cycles were constant load amplitude and sinusoidal in shape, and applied at a frequency to reflect prototype drainage conditions during cyclic loading in a typical offshore sand.

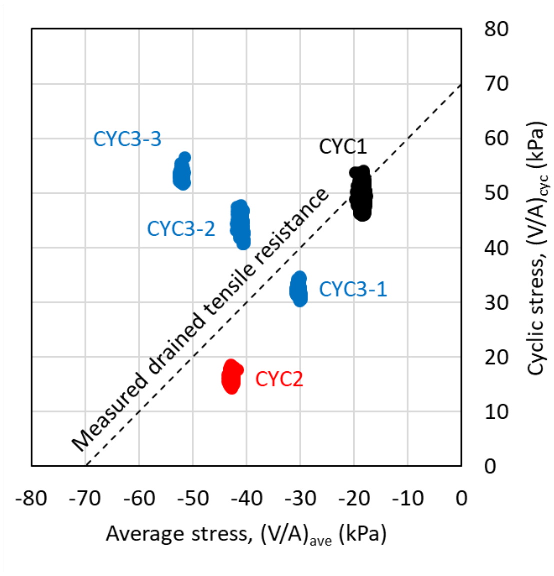

Figure 20. Caisson cyclic testing program

A summary of the results from CYC1 and CYC2 is presented in Figure 21, showing:

- Average and cyclic stress applied to the bucket, $(V/A)_{ave}$ and $(V/A)_{cyc}$ (top).
- Average and cyclic excess pore pressure measured underneath the bucket lid normalised by the respective applied stress, Δu_{ave} and Δu_{cyc} (middle).
- Measured displacement normalised by skirt length, and shown as a percentage, $\Delta z/L$ (bottom).

In the case of low average / high cyclic stress (CYC1), the results show an initial increase in average (negative) excess pore pressure ratio inside the bucket, which leads to slight upward movement. However, the Δu_{ave} dissipates (to zero) with continued cycling, and after around 100 cycles the upward movement stopped (with then very slight downward movement as cycling continued). The cyclic pore pressure stays at around 30% of the applied cyclic load, with the residual load taken by skirt friction – and after around 300,000 cycles the test was terminated without significant uplift displacement.

The test with high average / low cyclic stress (CYC2) showed even greater stability – with little (to no) average pore pressure observed inside the bucket, and no significant upward (or downward) movement over nearly 80,000 cycles.

Overall, it can be concluded from these tests that suction buckets can sustain average tension without leading to large movement (or failure) – confirming there is potential to optimise their design.

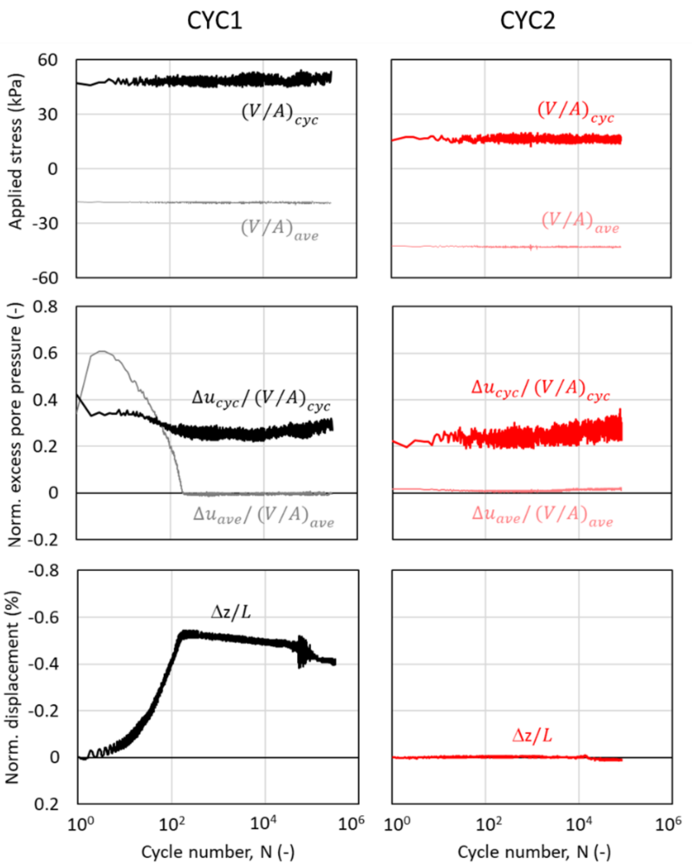

Figure 21. Cyclic response (CYC1 & CYC2)

Aside from average movement of the bucket, it is important to also consider foundation stiffness – as this influences the natural period of the jacket. Figure 22 presents results from CYC1 and CYC2 – and while the former shows some 'ratcheting' during the first 100 cycles, the stiffness within each cycle is high for both tests – despite the application of loads approaching the drained tensile capacity of the bucket.

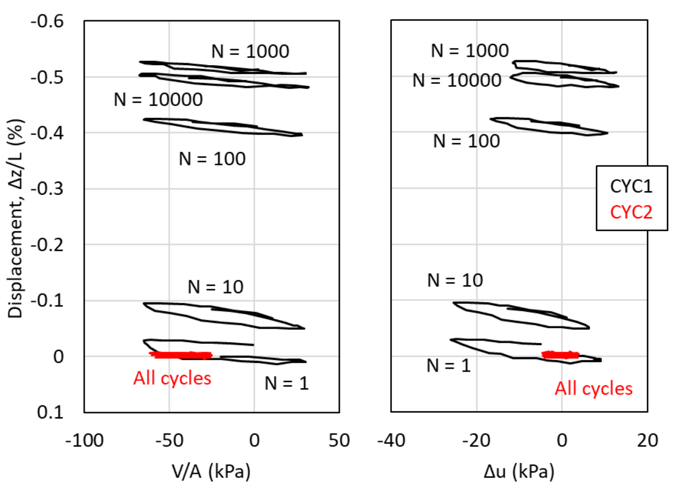

Figure 22. Observed foundation stiffness (CYC1 & CYC2)

After the completion of cycling, the bucket was subject to drained uplift to investigate whether there had been any change in capacity caused by cyclic loading. Figure 23 compares the monotonic result with the post-cyclic test in CYC2 (displacement plotted from the end of cycling) – and shows an increase in peak uplift capacity after cyclic loading (by around 15%), with high initial stiffness. However, with ongoing extraction the two responses align.

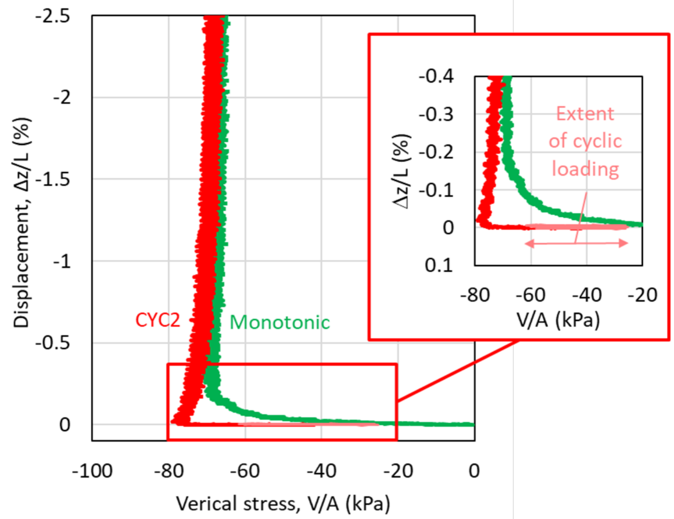

Figure 23. Post-cyclic monotonic response

The third test (CYC3) was designed to explore the boundary at which failure of the bucket (represented by continuous displacement) would be initiated. Figure 24 summarises the results from the three stages of CYC3. In each stage the average and cyclic vertical stress were kept approximately equal (i.e. 1-way loading) – applied at roughly 45% of R_d (CYC3-1), 60% of R_d (CYC3-2) and 75% of R_d (CYC3-3).

The first packet showed a similar trend to CYC1, with low average excess pore pressure (Δu_{ave}) initially observed, which dissipated with further cycling. The second packet was similar, albeit with lower Δu_{ave}. In both stages the bucket was stable over the full 10^3 cycles. However, the third packet showed a different response – and after only 10 cycles the average (negative) pore pressure started to increase, with a corresponding increase in upward movement of the bucket.

Based on this observation, the 'failure' load combination is interpreted as being between the second and third stages (i.e. CYC3-2 and CYC3-3). While this represents a maximum applied uplift (average plus cyclic) that exceeds the monotonic drained capacity shown in Figure 19, it is noted that the maximum applied stress in CYC3-2 is roughly equal to the higher drained resistance observed in Figure 23 – suggesting that drained uplift, hardened by cycling at modest stress levels, may in fact be the governing criteria. More testing is required to confirm this finding at different levels of 'wayedness' (the ratio of cyclic to average stress) – but even at this stage the results support a finding that it is conservative to assume buckets cannot withstand cycling about average uplift stress.

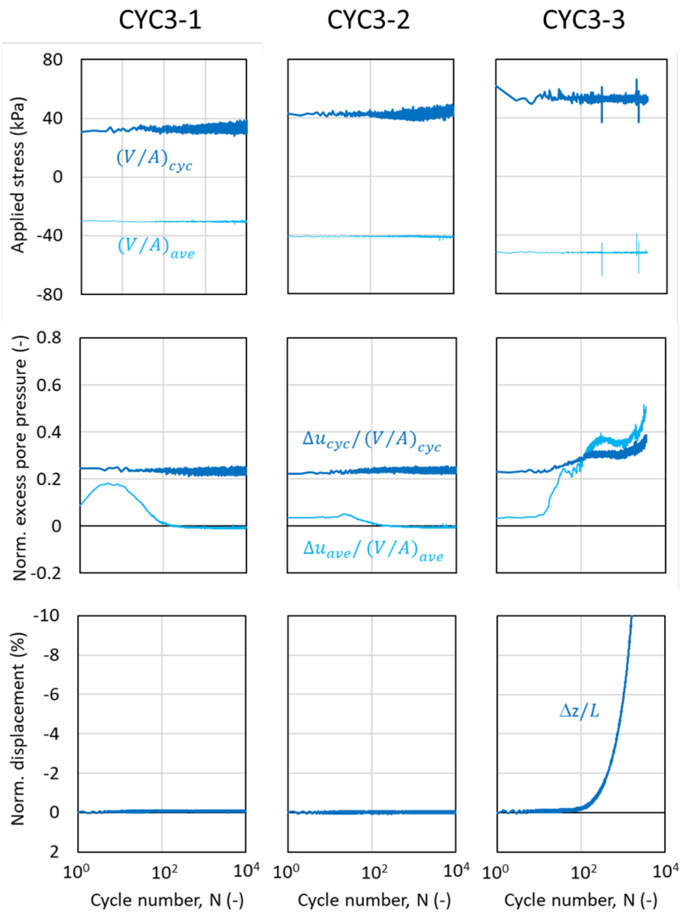

Figure 24. Cyclic response (CYC3)

5.3 *Outcome*

This final case study sought to justify the use of suction buckets when subject to prolonged uplift loading, in order to expand their use in jackets supporting offshore wind.

Model testing confirmed that it is possible to apply uplift loads – both average and cyclic – without triggering significant foundation displacement, provided the maximum applied stress stays within the drained uplift resistance. Tests were performed to a high number of cycles (on the order of 10^5) leading to high confidence in the findings. As the use of suction buckets was already at a high TRL, the results in this case are primarily used for technology optimisation to support increased use (at maintained TRL).

6 Concluding remarks

The objective of this paper was to highlight that there are numerous geotechnical challenges associated with the energy transition, and that these challenges can be addressed through centrifuge modelling. The discussion is supported by results from three case studies:

- The first involved suction (seepage) assisted driving of monopiles, which is proposed as a means of lowering blow count and reducing marine noise. This is considered at a low TRL and well suited to rapid prototyping in the centrifuge. Results suggest that this concept warrants further study, with residual questions being – can we control the process to minimise blow count? Is it practical for offshore use?
- The use of plate anchors in sand is considered an intermediate TRL opportunity, with centrifuge testing used to expand their use in a wider range of soils. The results show that suction-assisted installation is possible at low (and realistic) self-weights – but only by adjusting the position of the anchor. Sensitivity to flow rate is identified as an installation risk which must be managed. Can we now widen the scope of testing to cover more soils, potentially leading to widespread adoption of this cost-effective anchoring solution?
- Suction buckets are at a high TRL, having been used in the oil and gas sector for decades, and with existing experience in offshore wind. However, there remains uncertainty in regards their performance when subject to prolonged uplift in sand – and the centrifuge testing presented here aims to dispel these concerns. Following positive results, is this sufficient to enable broader use – or is more (possibly project specific) work warranted?

Overall, it is hoped that this paper has demonstrated how centrifuge modelling can play a key role both in progressing technology towards adoption, and through design optimisation. Coupled with numerical/analytical studies, and informed by appropriate understanding of soil parameters, such modelling can be a key inclusion in the 'toolkit' of a geotechnical engineer.

7 Acknowledgements

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