Geotechnical considerations associated with offshore renewable energy installations

Britta Bienen[1], C. Gaudin[1], and Mark F. Randolph[1]

[1] Centre for Offshore Foundation Systems, Oceans Graduate School, University of Western Australia, 35 Stirling Highway, Perth WA 6009, Australia.

ABSTRACT

Geotechnical considerations for offshore renewable energy installations differ from those associated with the oil and gas industry, and also according to the energy source. Important aspects include the eigenfrequency, absorption of extreme loading and the response to long-term multi-directional cyclic loading. The economics of offshore renewables require innovative foundation and anchoring solutions. This paper discusses recent developments addressing common design issues and provides a perspective on future research directions.

Keywords: renewable energy; offshore; geotechnical design; piles; suction bucket; cyclic loading

1 INTRODUCTION

The world is transitioning to energy generated from renewable sources, including wind, solar and wave. This paper focuses on geotechnical considerations associated with offshore wind and wave energy installations.

Technologies and markets globally are at different stages of maturity. For instance, bottom-fixed wind turbines may be supported by different foundation concepts but generally feature a tower with the nacelle and a 3-bladed rotor assembly, whereas concepts for wave energy devices vary widely. The majority of offshore wind turbines are supported by monopiles (approximately 87%), with recent developments in the north Sea including the first suction bucket jacket (Fig. 1) supported offshore wind farms.

Fig. 1. Offshore wind turbine supported by suction bucket jacket (source: DEME Group).

Offshore wind turbines (OWTs) are generally designed to have a system eigenfrequency that falls into the narrow window between the forcing frequencies of the rotor (1P) and blades (3P) in order to avoid resonance. Wave energy converters (WECs), on the other hand, are designed to resonate at the peak frequency of the energy in the wave spectra to ensure optimum power take-off (PTO). This may result in complex loading regimes of very high magnitudes, especially if the foundation is used as a reaction point that is shared by multiple devices (Fig. 2).

The overall capacity of all wind turbines installed worldwide by the end of 2018 reached 600 GW, with 53,900 MW added in 2018 alone (WWEA 2019). European markets have matured and stronger growth has now been observed in countries such as China, India, Brazil, USA, many Asian markets and also some African countries (WWEA 2019). In contrast, wave energy is still in a nascent stage. Noticeable trials include the Ocean Power Technology floating wave energy device, which has been tested off the coasts of Hawaii, USA (PhysOrg, 2016) and Scotland in water depths of up to 30 m since 2005, and the Perth Wave Energy Project (Fievez et al, 2015) of Carnegie Wave Energy, with three 240 kW WECs operating over 12 months offshore Garden Island in Western Australia. These small projects have aimed to demonstrate concept feasibility such that commercial developments can be expected in the coming decades. The industry will need to transition from single or small-array demonstrator units (of moderate scale and power capacity) towards integrated arrays (Fig. 2) of larger, full-scale devices to realise commercial energy generation.

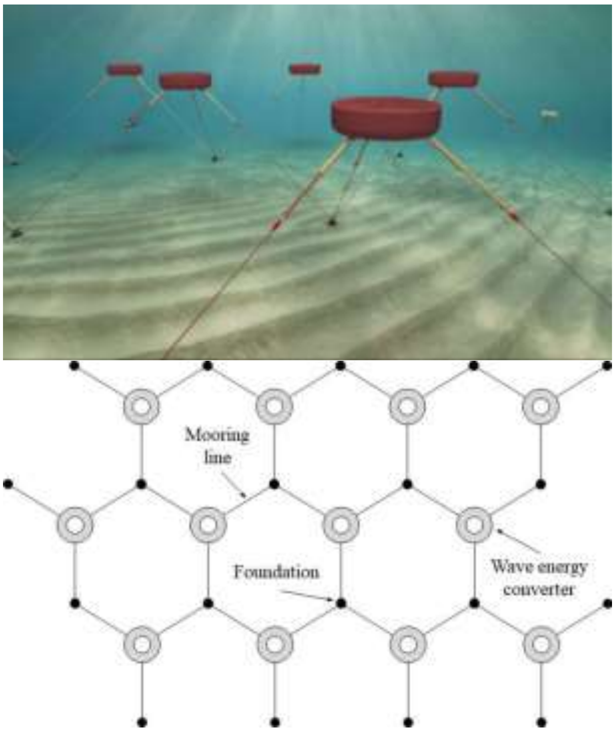


Fig. 2. Wave energy converter array with multiple moorings (top, source: Carnegie Clean Energy), schematic plan view of array (bottom).

Foundations or anchoring systems can contribute up to 25% of the development cost of offshore wind farms, and up to 30% of the total installed cost of a wave energy converter. Technological improvements and economies of scale, with wind farm developments featuring ever larger numbers of more powerful turbines, have resulted in substantial reduction in the levelised cost of energy (LCOE). The cost of offshore wind investments has fallen steeply over recent years. The price per megawatt is down 44.5% from €4.41 million/MW in 2013 to €2.45 million/MW (Wind Power Offshore 2019). Without large commercial scale installations, the cost of wave energy is harder to forecast and varies significantly between the various types of converters (and capital cost) and between forecasters. For an array of 100 point absorbers, the cost has been estimated at around US$800/MWh (Neary et al. 2014), although a case study using an oscillating water column offshore Portugal estimated a cost as low as US$86/MWh (Castro-Santos et al. 2015).

While lessons from the offshore oil and gas industry have been useful for the emerging offshore renewable energy industry and many guidelines are borrowed from the oil and gas industry, there is a limitation to transferability due to the differences in challenges. Some of those relevant to geotechnical engineering are discussed below.

- New environments

Coarse-grained soils are prevalent in shallow water where most offshore renewable energy developments have taken place to date, and challenging conditions (including weathering horizons, scour and shifting sand beds) are frequently encountered. Seabed conditions in new regions of offshore wind energy development include layered, weakly cemented or micaceous soils perhaps with shallow bedrock. These pose additional challenges compared with conditions in the North Sea, which has seen most of the early offshore wind development. The shallow water itself contributes to geotechnical considerations as the resistance of saturated sand to rapid shearing is limited by cavitation, which occurs at a lower absolute pressure in shallower water.

- New loading regimes

The high energy shallow water environment can lead to extreme dynamic loads that may affect survivability of renewable energy systems. The wave (and wind) loading varies in magnitude, with different metocean conditions resulting in different eccentricities (or distance to the seabed) of the resulting environmental load acting on the system. The self-weight of renewable energy systems is typically low. Further, loading on the foundations is likely to be multi-directional, either through seasonal variations in the direction of the prevailing weather systems passing through or because a foundation or anchor secures multiple renewable energy converters.

- New design considerations

Foundations for offshore renewable energy converters must withstand the ultimate loading conditions at a site, but will probably be exposed to relatively low level loading for the majority of their in-service life. Serviceability criteria are often critical in the design of offshore renewable energy systems, with out-of-verticality of the dynamically sensitive OWTs typically limited to 0.5° (DNV 2016). This places strong emphasis on accurate assessment of the low strain stiffness of foundation sediments, and also the cumulative effects of tens of millions of loading cycles. Field measurements of offshore wind turbines have shown differences in the eigenfrequency compared to the design (Kallehave et al. 2015; Arany et al. 2016), with most of the uncertainty attributed to the foundation-soil interaction. This necessitates further advances in geotechnical understanding. The resistance to extreme loading of WECs requires innovative solutions that satisfy safe, reliable yet economical design. These should address both the geotechnical capacity, but also mechanical design to minimise extreme loads.

- New economic constraints

Previous offshore wind farm developments were subsidised, but new developments now need to prove themselves competitive with other energy sources. Offshore wind farms may feature upwards of 200 OWTs, such that small savings per foundation quickly multiply to significant economic benefits, which may be decisive for the financial viability of a new development. The economics of offshore renewables require innovative foundation and anchoring solutions. For offshore wind farms in areas with competent seabed sediments, large diameter monopiles still dominate, but in deeper water jacket structures become optimal. For wave converters, arrays of devices allow sharing of each anchor among multiple devices. This results in new loading regimes but with the advantage that each device connected to a given anchor is unlikely to experience the peak design conditions simultaneously.

This paper presents a snapshot of recent research addressing geotechnical design considerations from installation and in-service performance through to survivability under extreme loading.

2 INSTALLATION

The geotechnical performance of foundations relies on their penetration to target depth during the installation process. Offshore, this is usually achieved by a penetration process from the seabed, which is typically performed through impact driving of large diameter open-ended cylindrical monopiles or jacket piles, or with the assistance of a pressure differential generated through a pump on a suction bucket, after initial self-weight penetration. The original in-situ soil state may be changed significantly due to the foundation installation process, and this may affect in-service performance. This section focuses on two aspects: the physical processes occurring during suction bucket installation and the effects of pile installation on foundation performance.

2.1 Visualisation of suction bucket installation

Suction bucket installation consists of two phases, the initial self-weight penetration and the suction assisted penetration. In clay, the differential pressure in essence constitutes an additional driving force that, together with the self-weight, is used to install the foundation. In sand, which is significantly more permeable, the reduced water pressure from pumping also creates seepage flow from the external soil, around the skirt tips and upwards through the suction bucket interior. This reduces the effective stresses at the skirt tips, thus facilitating suction bucket installation even in dense sand. Suction caissons have been used successfully for some time in the oil and gas industry (Eide & Andersen 1984; Tjelta et al. 1986; Hansen et al. 1992; Bye et al. 1995; Erbrich & Tjelta 1999; Andersen et al. 2005) and are increasingly considered as foundations for offshore renewable energy installations (Tjelta 2015).

Prediction methods exist for suction bucket installation into sand (Houlsby and Byrne 2005; Andersen et al. 2008; Senders and Randolph 2009) and clay (Andersen et al. 2005; Houlsby and Byrne 2005), and these have been shown to predict measured installations well (e.g. Collia et al. 2007 in clay; Andersen et al. 2008 in sand). However, these were Class C predictions where the installation response was known. This masks uncertainty introduced by parameters underpinning the predictions including the ratio of internal to external permeability (where a value greater than one indicates loosening of the soil plug). Some of the uncertainties can be minimised through detailed understanding of the effects of the suction installation process on the soil state.

In order to obtain physical evidence of the changes within the soil body during suction bucket installation, an experimental methodology was developed on the basis of particle image velocimetry (PIV) analysis performed on images captured during the installation of half a suction bucket against a transparent window, with the tests performed in a geotechnical centrifuge (Ragni et al. 2019). This allows visualisation and quantification of changes in soil state during suction bucket installation. The methodology was validated in sand before being applied more recently to complex layered soils. Performance of these challenging experiments in a geotechnical centrifuge is important to ensure the stresses, and hence the soil response, reflects that in the field. Executing these experiments at small scale on the laboratory floor significantly simplifies the test but it is difficult to achieve in situ void ratios and sand strengths that can be related to the field.

As expected, the deformation mechanism governing the suction assisted phase shows a preference for the soil below the skirt tips to move inwards and upwards inside the bucket. This contrasts with the initial self-weight penetration, during which the soil flow is divided more equally between the inside and outside of the advancing skirt (Ragni et al. 2019). Figure 3 shows the total shear strain γ_s during the suction-assisted penetration phase into dense sand.

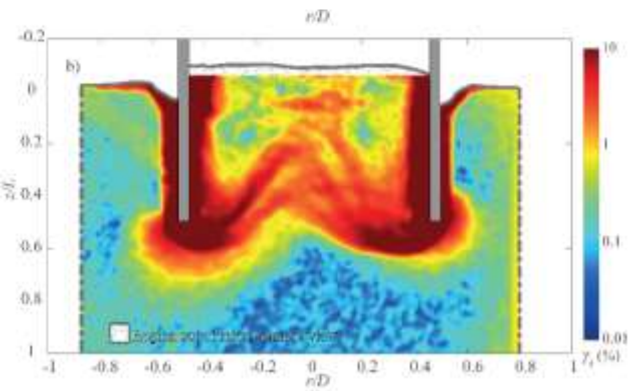


Fig. 3. Total shear strain γs (%) contours during suction-assisted installation in dense sand (Ragni et al. 2019a).

While suction-assisted installation in dense sand has the effect of reducing the relative density of the sand within the suction bucket, and consequently increasing its permeability, sand dilation appears to be only a minor contributor to soil plug heave. The main cause of plug heave in the experiments was identified as soil displaced by the penetrating skirts.

Having demonstrated the viability of investigating suction bucket installation in a centrifuge environment with PIV analysis of the images, the methodology may be applied to obtain physical evidence of the processes governing suction bucket installation in layered soils where the concern is that a low permeability (clay) layer may prevent seepage flow within a sand layer, thus denying the reduction of tip resistance required for successful installation.

Senders et al. (2007) postulated that seepage flow in a sand layer may be established as a result of a crack through a clay layer or through uplift of the overlying clay layer within the suction bucket skirts. A large number of trial installations in the field, preceding the offshore wind farm developments with suction bucket jackets in the North Sea indicated the possibility of successful suction bucket installation even in layered soil, but the mechanisms remained poorly understood.

Results of a recent centrifuge PIV testing campaign confirmed that suction was transferred to the underlying sand layer through uplift of the clay plug (Fig. 4), once the clay plug weight was overcome. The clay plug uplift was not always symmetrical in the tests. Clay plug uplift did not cause premature termination of suction bucket installation in the tests, but it has the potential for premature refusal once the clay plug reaches the suction bucket lid invert, as also commented by Watson et al. (2006).

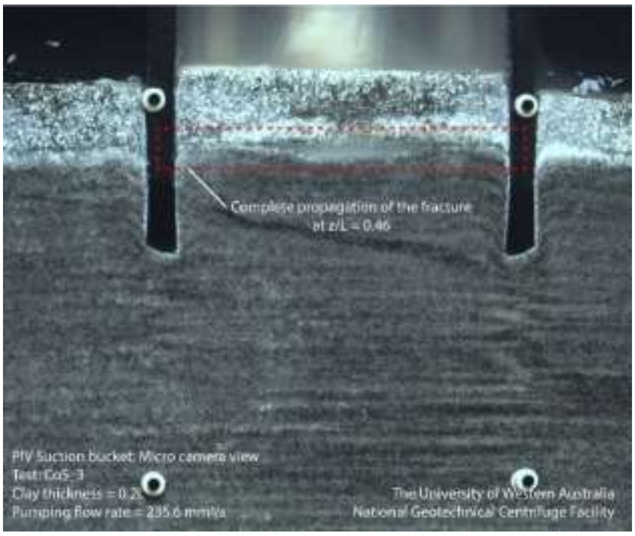


Fig. 4. Uplift of clay layer enabling suction to be transferred to the underlying dense sand.

Further research is required to characterise the effects of suction bucket installation on the in-service performance of the foundation. The centrifuge experimental results of a suction bucket installed into very dense sand at pumping flow rates spanning three orders of magnitude did not suggest significant effects of the installation history on the foundation performance under vertical cyclic loading (Bienen et al. 2018a). Further, a permeability ratio of 1 provided prediction of the suction installation that was in good agreement with the experimental measurements, indicating no significant loosening of the soil plug. Results from a further centrifuge testing campaign indicate that any soil plug loosening may be temporary and suggest that the pressure applied through the lid affects the stress state of the plug (Stapelfeldt et al. 2018). However, the role of the lid contact on in-service suction bucket performance is not yet well understood.

2.2 Effects of monopile installation process

Monopiles are typically installed by impact driving, although vibratory driving has also been used. The adjacent soil is displaced in order to accommodate the steel wall, and is also subjected to many shearing cycles. In sand this leads to significant changes in the stress field and the void ratio in the soil affected by the installation process. A common research focus has been on characterising the development of arching stresses inside cylindrical open-ended piles penetrated into sand (through physical modelling, e.g. Henke and Bienen 2013, or through numerical modelling, e.g. Ko et al. 2016), which may lead to arching stresses developing in the soil inside the pile. An earlier series of centrifuge model tests established the importance of the in situ soil state – the combination of density and stress level – on the capacity of piles in sand (Klotz and Coop 2001).

Figure 5 shows void ratio changes down the pile shaft in medium dense sand following 10D of jacked pile installation from a pre-installation depth of 10D, at different distances from the pile. These results were obtained from numerical modelling using the material point method (MPM) with a hypoplastic relation to reflect the sand behaviour (Phuong et al. 2016). The numerical analyses of the pile installation show significant differences in the soil stresses and void ratio (Fig. 5) around the pile after installation compared with the in situ state.

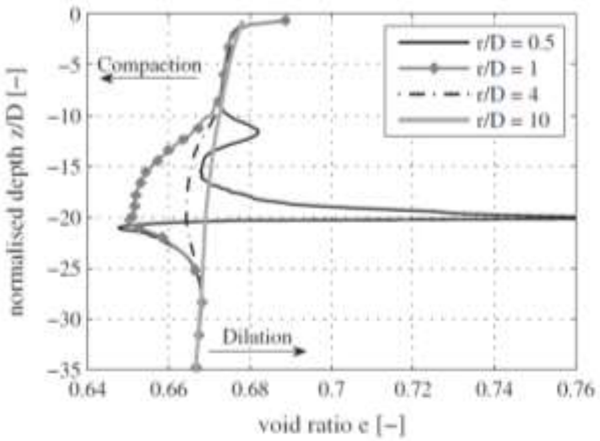


Fig. 5. Void ratio changes following jacked pile installation (Phuong et al. 2016).

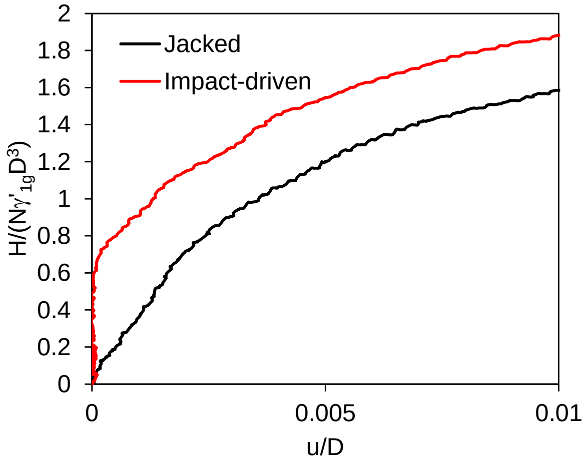


Fig. 6. Pile lateral loading following jacking or impact-driving (Fan 2019).

Consideration of the effect of the pore fluid response in saturated sand, resulting in soil liquefaction around the penetrating pile during impact or vibratory-driven installation, was made possible using a 2-phase formulation in MPM analyses (Galavi et al. 2017). Although the pile was penetrated by less than one diameter from its pre-embedment due to the computational expense of the analyses, these initial results demonstrate the potential of this numerical approach to capture the relevant physical processes occurring and hence allow additional insights to be gained, including void ratio distribution and stress field in the soil domain. This information is difficult to obtain from physical modelling, which tends to be limited to point measurements, although sensor technology continuously develops.

Changes in the in situ soil state due to pile installation have the potential to influence the in-service foundation performance. The importance of this aspect is highlighted by the probability of large numbers of relatively low magnitude (dynamic) loading, the response to which is governed by the post-installation low strain response of the soil and is critical for maintaining serviceability.

Figure 6 shows effects of the installation process on the initial stiffness when the pile is subject to lateral loading (although overly stiff initial response may have resulted from extrapolation to the pile head of the near zero displacements measured by the two linear displacement transducers). The experiments were performed in a geotechnical centrifuge and showed significantly higher initial stiffness following impact driving compared with jacked installation in medium dense sand. This is important as the target range of eigenfrequency in order to avoid resonance is narrow in the design of offshore wind turbines. This necessitates accurate predictions of the foundation stiffness, both initially and as it evolves during the operational life, with little room for uncertainties or conservatism.

Physical evidence like this can be used to validate numerical models. Lateral loading of a pile performed in numerical analyses, commencing with the soil state resulting from the installation process, can then provide insights into soil response details underpinning foundation performance. Figure 7 shows an example void ratio distribution following impact-driven pile installation from the soil surface into medium dense sand. The contours illustrate the extent of sand densification due to the pile installation process, which was modelled here using CEL with a hypoplastic constitutive model to capture void ratio changes in the sand. The lateral loading phase can be modelled more economically using a small strain approach, to which the state variables determining the current conditions in the soil domain are mapped. This follows a similar approach employed in Class A predictions of lateral pile response following impact or vibratory driven installation (Heins and Grabe 2017).

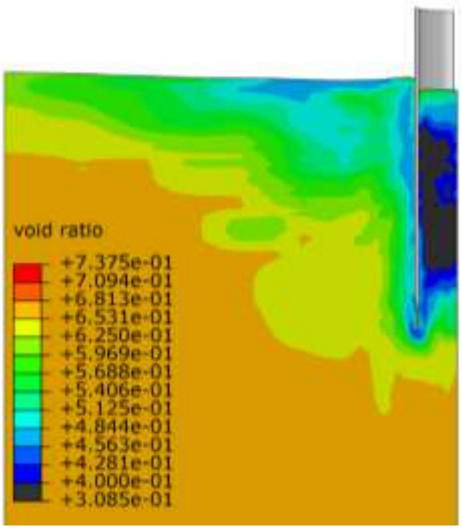


Fig. 7. Example void ratio distribution following impact-driven pile installation into medium dense sand (Fan 2019).

This is an area of intense ongoing research internationally, with anticipated significant advances in the near future that will inform the development of improved prediction methods and recommendations.

3 PERFORMANCE

Following the successful installation, the foundations of offshore renewable energy installations must withstand millions of load cycles, which vary depending on the metocean conditions, and of course resist the ultimate design loads.

3.1 Suction bucket combined capacity for offshore wind turbine

Suction buckets are considered increasingly as potential foundations for offshore wind turbine, due to their ease of installation and low cost. As discussed above, current research is being undertaken to understand the effect of suction installation on the original in-situ stress state and the associated strength and stiffness. For monopod suction buckets considered as an alternative to monopiles, there are additional concerns associated with the combined vertical V, horizontal H and moment M capacity under the low vertical loads typical of offshore wind turbines. The loading regime is rather different from those for deep-skirted foundations designed for oil and gas applications.

For shallow foundation with no skirts or shallow skirts (i.e. with L/D < 0.5), there has been an increasing trend of calculating capacity under combined V-H-M loading using "interaction diagrams", which draw a locus of failure states in load space (e.g. Roscoe and Schofield 1956; Butterfield and Ticof 1979). Extensive work has been conducted (Houlsby 2016) for drained soil conditions (e.g. Nova and Montrasio 1991; Gottardi et al. 1999; Bienen et al. 2006), and for undrained conditions (e.g. Salencon and Pecker 1995; Bransby and Randolph 1998; Martin and Houlsby 2000; Gourvenec and Randolph 2003) to express the plastic response of the foundation in terms of force resultants (V, M, H), which allows the model to be coupled directly to the structural analysis (e.g. Houlsby and Cassidy 2002; Bienen and Cassidy 2006; Zhang et al. 2014).

Two hypothesises are usually assumed in the development of plasticity models (e.g. Gottardi et al., 2005): (1) a fixed shape for the yield surface and (2) a work-hardening of the yield surface scaling its size based solely on the vertical plastic displacement (w_p) of the foundation. These hypothesises have been validated in previous investigations mostly for surface footings under high vertical loads. However, few studies based on this approach have focused on the behaviour of higher aspect ratio suction buckets, in sand, and subjected to more typical low vertical loads.

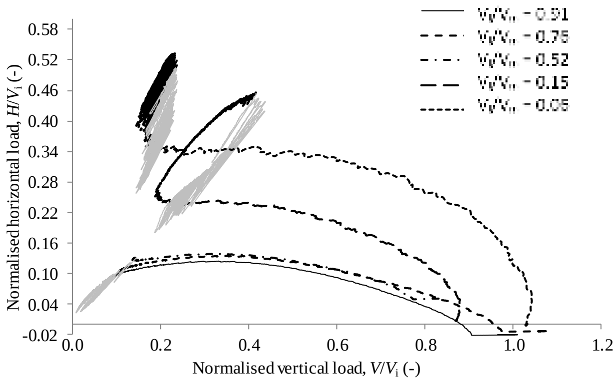


Fig. 8. Swipe test results for a suction bucket with aspect ratio L/D = 1. Both the horizontal and vertical loads are normalised by the initial vertical load V_i with the legend showing this as a ratio of the maximum vertical load V_m (after Zhao et al., 2019).

These have been checked recently through a series of model tests in dry sand involving a suction bucket with an aspect ratio L/D of 1 subjected to various load paths including swipe test (i.e. pure horizontal displacement under constant vertical displacement, with zero rotation enforced) and radial tests (i.e. moving the bucket at constant displacement ratio δ_u/δ_w from an initial loading state, still with zero rotation) (Zhao et al. 2019). The former enables identification of the yield surface, while the latter provides information about work hardening.

Results of swipe tests are presented in Figure 8 in the V-H space, for which both loads have been normalized by the initial vertical load V_i at the initiation of the swipe, which varies from 0.06 to 0.91 times the maximum vertical capacity V_m.

Figure 8 shows (i) that the V-H yield surface does not scale isotropically with reducing vertical load and (ii) an increase of both vertical and horizontal loads at low vertical loads for low initial vertical loading V_i, which is subsequently followed by a softening response. Both observations suggest that the assumption of a fixed shape of the yield surfaces for caissons in sand under different vertical loading levels is incorrect. Also, plastic hardening may occur due to dilative sand response without change of foundation penetration. Similar hardening due to dilation has been reported by Fiumana et al. (2019).

Closer examination of the test performed at V_i/V_m = 0.15 in Figure 9 (now normalised by V_m) reveals that the load path followed at large horizontal displacements (i.e. from A to B, when V has reduced to its minimum value before increasing again) can be approximated by a capacity line that assumes a simple failure mechanism involving shearing at the base of the caisson, passive soil resistance at the front of the caisson and active soil resistance at the back, with a friction angle equal to the peak friction angle. This mechanism is different to the Brinch-Hansen mechanism that would be assumed for shallow skirted foundation and caisson under high vertical load and zero rotation.

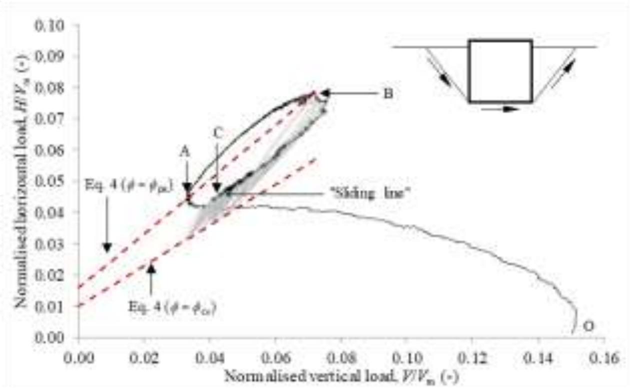


Fig. 9. Focus on the swipe test results at $V_i/V_m = 0/15$ emphasising the concomitant increase of vertical and horizontal load at large horizontal displacement (after Zhao et al., 2019).

The increase of V and H for the load path from point A to B (and back to C) in Fig. 9 is apparently a hardening (and then softening) process, which occurs without any change of penetration of the foundation (as enforced during a swipe test). Consequently, the common assumption about the work-hardening of yield surfaces solely relating to the plastic vertical displacement cannot explain the results observed.

A revised hardening law was then proposed for which the plastic capacity of the caisson (and the size of the whole yield envelope) is controlled by horizontal plastic displacement in addition to penetration. This resulted in an improved yield surface formulation for bucket foundation under low vertical load, the complete description for which is provided in Zhao et al. (2019) and which is illustrated in Figure 10. All the yield envelopes now collapse onto a single one, where the horizontal and vertical loads are normalized by an updated V^*_0 that incorporates hardening arising from plastic horizontal displacement. It is also noteworthy that the envelopes are not symmetrical along the vertical axis (as is that formulated by Gottardi et al. 1999 for surface footing in sand, for instance). The peak horizontal capacity is mobilized at a normalized vertical load of about 0.3, reflecting the importance of the lateral resistance in the caisson capacity, as inferred from the soil failure mechanism discussed above.

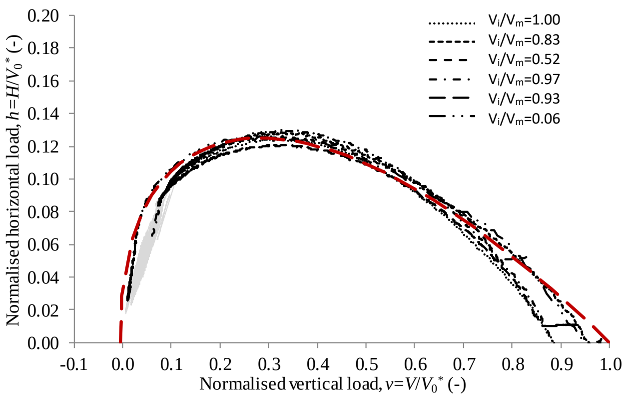


Fig. 10. V-H yield envelopes for suction bucket in sand for vertical load ranging from 0.06 to 1 the maximum vertical bearing capacity V_m (after Zhao et al., 2019).

Further centrifuge testing results, obtained with skirt length to diameter results of 0.25 and 0.5 and different combinations of horizontal and rotational movement applied during the swipe tests, elucidate the complex effects of the interaction of skirt aspect ratio and relative stress level on the VHM yield surface (Fiumana et al. 2019).

3.2 In-service response of offshore foundations

Loading of offshore foundations is characterised by a large number of cycles. The wind and wave actions on offshore wind turbines result in horizontal and moment loading of single foundations (monopile or single 'monopod' suction bucket), while the moment loading on multiple footings (e.g. supporting a jacket) is predominantly transferred via a vertical push-pull mechanism.

Large number of load cycles

Cuéllar et al. (2012) illustrate through carefully collected evidence from small scale experiments the physical phenomena of macro-mechanical densification (i.e. an overall reduction of intergranular voids) and convective granular flow around a monopile in response to large numbers of lateral cyclic loading (Fig. 11). The resulting progressive stiffening of the surrounding soil may modify the pile eigenfrequencies, which may impact on the susceptibility to dynamic resonance of the offshore wind turbine system.

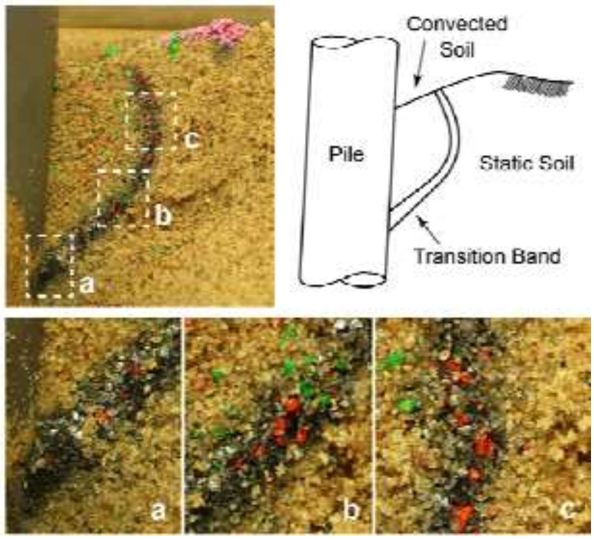


Fig. 11. Evidence of convective granular flow around a monopile in response to large numbers of lateral loading cycles (Cuéllar et al. 2012).

The trend of the foundation displacement (or rotation) accumulation has largely been characterised by exponential expressions fitted to experimental data for monopiles (e.g. LeBlanc et al. 2010) and monopod suction buckets (e.g. Zhu et al. 2013). In order to predict the accumulation, rather than the trend only, the initial response to the first loading cycles is required to be known. In this, the soil state following installation is important as discussed above. Zhu et al. (2018a) provided quantification of the initial response on the basis of centrifuge tests of monopod suction buckets (also comparing with jacked installation, which is the common mode of installation in the databases available in the literature) and link the accumulation response with data under long-term cyclic loading.

Ordering of cyclic loading for geotechnical design

Accumulation trends for deformations are typically provided for a specific combination of cyclic load amplitude and cyclic symmetry (i.e. one-way, two-way or asymmetric two-way cyclic loading) as well as a particular load eccentricity, which determines the ratio of moment to horizontal loading applied to the foundation. In practice, cyclic loading histories are divided into packets of similar cycles that are ordered by ascending magnitude (Sturm 2017), the response to which can be predicted by assembling the cumulative response to each of the packets.

Of course, the metocean conditions offshore are not ordered in this way over the lifetime of the offshore structure. However, for a small scale monopile model in sand subjected to approximately 10,000 cycles, Leblanc et al. (2010b) suggested that differences resulting from the ordering of the cyclic loading packets do not appear to result in significantly different final accumulated rotation (Fig. 12).

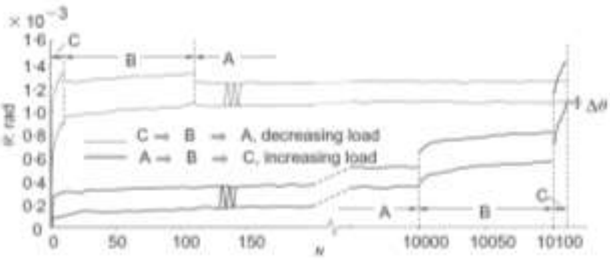


Fig. 12. Envelopes of monopile rotation due to packets of cycles with different amplitudes applied in different sequences (LeBlanc et al. 2010b).

By contrast, initial results from small scale tests of a suction bucket in sand involving a minimum of 10^6 cycles performed at the University of Western Australia indicate that the ordering of loading may indeed result in significant differences due to densification and possible rearrangement of grain contacts. This is not surprising and is in line with recent results from triaxial testing (Wichtmann and Triantafyllidis 2019). No doubt advances in x-ray tomography and discrete particle method (DEM) will contribute to advancing our understanding of these processes in the near future.

To predict foundation response under large numbers of load cycles, the high cyclic accumulation model (a combination of a few cycles actually modelled allowing forecasting of the subsequent response trend) developed on the basis of a tremendous database of soil element test results (Wichtmann and Triantafyllidis 2016a, b) is a promising approach with flexibility to cater for complex conditions. Through the availability of complete datasets, significant opportunity now exists to validate this approach for applicability to monopiles and suction buckets.

Cyclic loading into tension

The undrained foundation uplift capacity is limited by cavitation (Houlsby and Byrne 2005), as shown in centrifuge experiments (Bienen et al. 2018a).

The response to cyclic loading into tension as would be experienced by the windward foundation of a suction bucket jacket in sand has been shown to depend critically on the permeability (Fig. 13), with the resulting drainage conditions accounting for complex load transfer mechanisms (Bienen et al. 2018b).

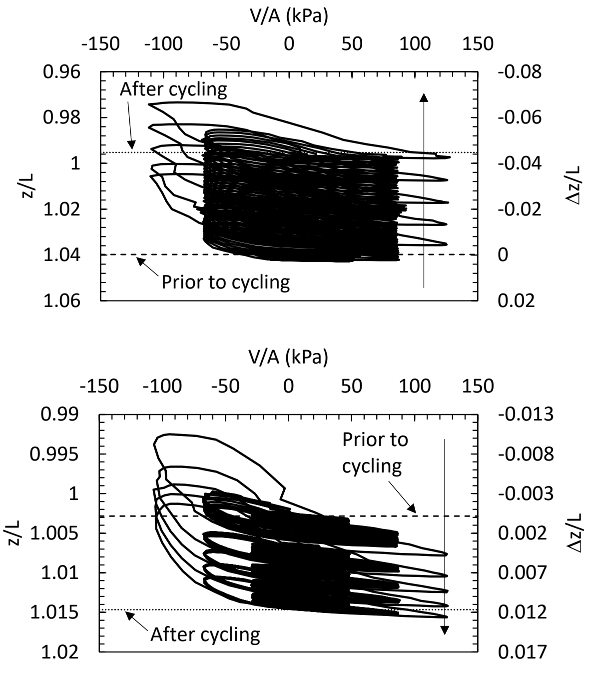


Fig. 13. Suction bucket response to vertical cyclic loading into tension resulting in uplift (top) or settlement (bottom), depending on the sand permeability (Bienen et al. 2018b).

Near zero movement was measured when the cyclic load remained below the drained frictional capacity, despite each of the 1,000 cycles applying tensile load. Cycling to approximately double the drained frictional tensile limit also resulted in insignificant movement of the suction bucket. The maximum applied cyclic load exceeded the drained frictional capacity by a factor of more than eight.

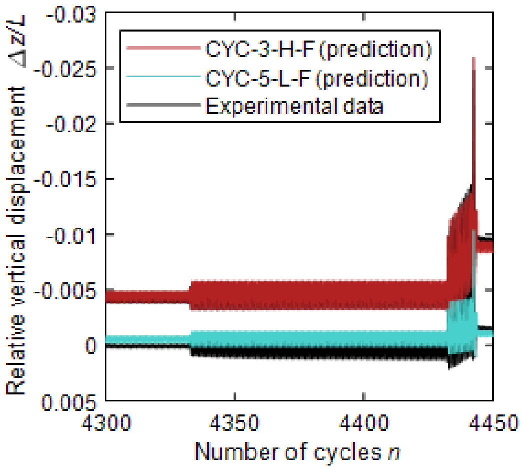


Fig. 14. Predicted history of vertical displacements during cyclic loading.

Stapelfeldt et al. (2019) added further data and proposed a simplified method to predict the response of suction buckets under cyclic vertical (compressive and tensile) loading, accounting for liquefaction and cavitation. The predicted response agrees well with centrifuge testing data as shown in an example in Figure 14.

Ongoing research focuses on suction bucket response in layered soils.

3.3 Multidirectional loading: stiffness and capacity

Monopiles to support offshore wind turbines, and anchor piles for floating wind or wave energy devices, are subjected to multi-directional loading during their operational life. It is therefore necessary to consider the effects of the varying load direction, relative to the purely in-plane response, on cumulative displacements and cyclic loading capacity.

At present, the effect of multi-directional loading has been explored mainly through experimental studies, both at the soil element level and also through model tests and small field-scale tests. Numerical developments for considering the effects of changes in load direction are now being developed and are discussed first, although it should be noted that such methods have yet to be calibrated against experimental data.

Numerical developments to date have focused on generalization of traditional beam-column analysis of piles, extending a uni-direction load transfer (p-y) response into multiple directions. An early contribution (Levy et al. 2007) adopted simple elastic-perfectly plastic response in two orthogonal directions, but with the limiting values of p_{ult} in the two directions at any given depth linked by means of a circular yield envelope. A variational approach was then used to solve the system of equations.

A more sophisticated version of the above is the bounding surface p-y (BSPY) model developed by McCarron (2015, 2016). Hypothetical load trajectories in two orthogonal planes showed that the resulting displacements were not parallel with the loading trajectory. In addition Levy et al. and McCarron showed a reduction in pile resistance mobilized at moderate displacements compared with similar uni-directional loading. The BSPY approach shows particular promise, once calibrated, for estimation of cumulative deformations under multi-directional cyclic loading.

More recently, a different approach has been suggested (Lovera et al. 2019), with multiple p-y springs distributed around the pile periphery. The form of each spring is similar to the particular underlying uni-direction load transfer curve required, but rules are given for how to adjust the model parameters to allow for the presence the distributed springs. The particular focus was on assessing the effect of changing load directions on the cyclic stiffness, hence natural frequency of the foundation and superstructure.

An extensive experimental study into the effects of multi-directional loading was carried out as part of the doctoral research of Rudolph (2014). The study combined insights from soil element tests, physical modelling at small scale at 1g, in the centrifuge and field tests as well as numerical modelling.

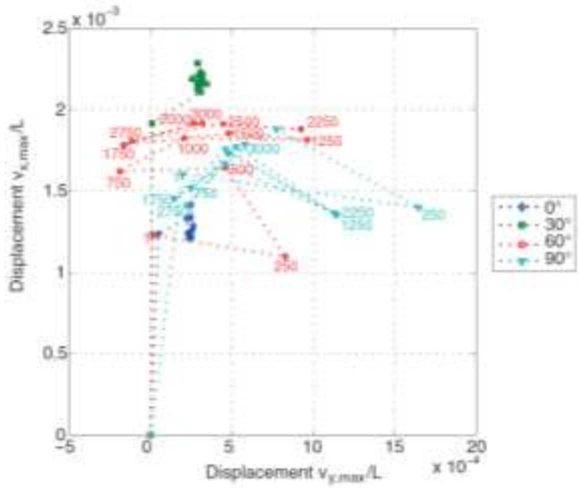
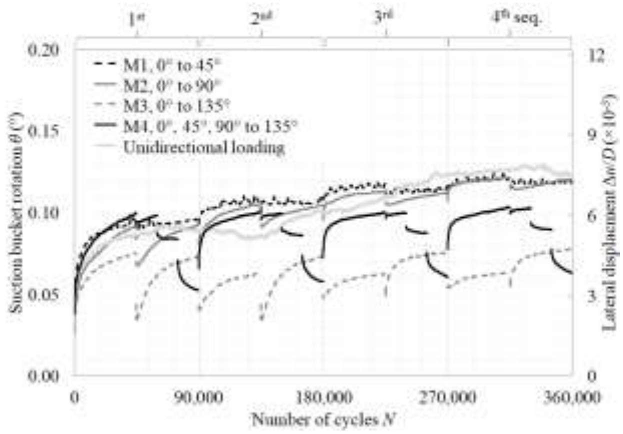


Fig. 15. Pile head displacement paths for tests with sinusoidal change of direction in dense sand, depicted at selected cycle numbers (Rudolph et al. 2014).

As an example, Figure 15 illustrates the pile head displacement paths for four tests. Sinusoidal cyclic lateral loading was applied, with the loading direction continuously varying over a range of 30°, 60° or 90°. For comparison, a uni-directional test (0°) was also included. The plot shows the two lateral displacement components, normalized by the pile embedment length. The displacement paths are shown at selected cycle numbers as annotated, corresponding to either a reversal in transverse loading direction (i.e., N = 250, 750 etc.) or loading along the centerline (i.e., 500, 1000 etc.). Additionally, the starting point and the first cycle response are also included. The test with uni-directional loading experienced very little displacement in the transverse direction as expected, whereas the 60° and 90° tests show a wider range of transverse displacement and overall a sideways drift. This becomes apparent when examining the points corresponding to loading along the centreline.

The observations overall indicated significant differences in the stiffness of monopiles between uni-directional and multi-directional lateral cyclic loading. Multi-directional lateral cyclic loading generally resulted in higher displacements and lower stiffness compared with uni-directional loading (Rudolph et al. 2014; Nanda et al. 2017), most likely due to shear deformation of a larger volume of soil mass adjacent to the pile. Neglecting the multidirectional loading effect therefore has the potential to lead to unconservative design (Su 2011; Rudolph et al. 2014).

In contrast to the above, the response to multi-directional lateral of a suction bucket installed in dense sand over stiff clay did not exceed that under uni-directional loading (Zhu et al. 2018), and the normalised unloading stiffness also evolves over a similar range (Fig. 16). Similar to the numerical findings (McCarron 2016), the resulting displacements gradually trend towards, but do not coincide with, the direction of load application. Further, the post-cyclic loading stiffness and ultimate capacity in the initial loading direction were found not to be significantly affected by multidirectional cyclic loading. This is unlike unidirectional loading where the consolidation of the clay layer increases both the stiffness and capacity (Zhu et al. 2018).



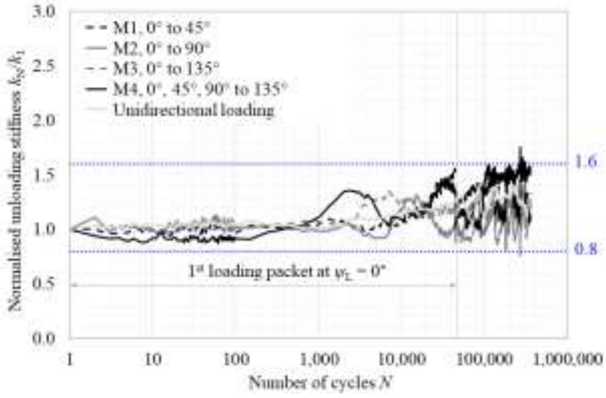


Fig. 16. Evolution of rotation (top), unloading stiffness (bottom).

Further research is ongoing to better understand the effect of changes in cyclic loading direction on foundation response.

4 SURVIVABILITY

4.1 Rationale

Offshore oil and gas structures were initially developed in shallow waters (<100 m), on continental shelves, before moving further offshore to water depths up to 3000 m with the depletion of shallow reserves. This required the development of compliant and floating structures that are still designed to avoid large accelerations. This has been achieved by ensuring that natural frequencies associated with the structure and mooring configuration are well below or above the band of energy-bearing frequencies present in wave spectra.

In contrast to oil and gas structures, floating renewable devices will be designed for much larger relative accelerations. In the case of wave energy devices this is essential, with many (if not all) floating devices needing to resonate at a frequency coinciding with the peak frequency of the energy in the wave spectra to ensure optimum power take-off. For offshore floating wind turbines differences in the risk appetite and serviceability requirements are also expected to result in commercial structures that may experience larger accelerations than conventional oil and gas facilities.

The more dynamic motion of floating renewable devices will result in different load characteristics and design challenges. Among those, dynamic conditions are of specific consideration as they may result in snatch loads on the foundations (i.e. at full extension of the mooring line or power take off) (Weller and Johanning, 2014). These loads can be large, but occur for only short duration.

Designing anchoring systems to resist extreme and dynamic loads is extremely costly and inefficient and strategies to avoid or reduce extreme loads need to be investigated to significantly reduce the size (and cost) of the anchoring system. This is notably the case for WECs using the mooring point as reaction point. This point is illustrated in Figure 17 that plots the probability of exceedance of the vertical load applied to a foundation by a spherical floating point absorber with a linear power take off subjected to a year of wave conditions at a location offshore Western Australia.

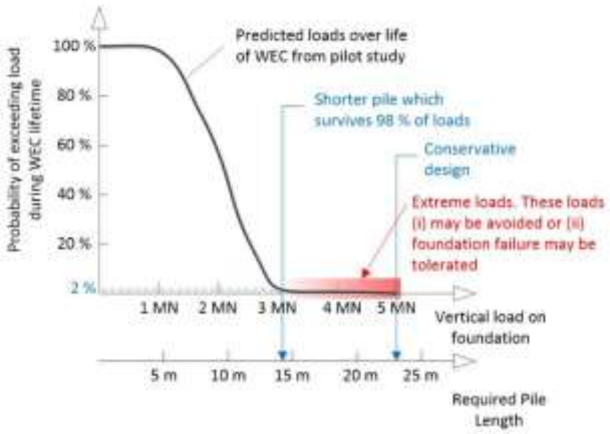


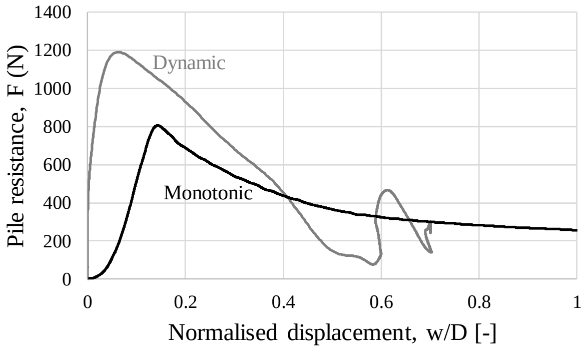
Fig. 17. Example of probability exceedance of foundation load applied by a floating point absorber over multiple years of operation.

A striking feature of Figure 17 is the length of the tail of the curve, which represents the relatively small number of very large load events resulting from the most extreme wave groups within the most extreme storms. Design approaches or technologies that would enable foundations to avoid or survive these extreme loads would reduce significantly the size (and cost) of the foundation. Resistance of pile foundations in sand under snatch loads and active suction mechanism to resist extreme loading are two research directions that are discussed further.

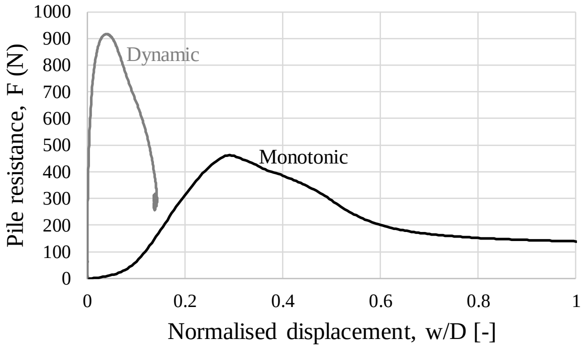
4.2 Resistance to dynamic loading

Snatch loads are dynamic events that occurs over a millisecond. The response of foundations to these type of loads is poorly understood, but has been investigated recently through a series of centrifuge tests that looked at the dynamic capacity of piles in dry and saturated sand under dynamic loads that exceeded the pile static capacity.

Example test results are provided in Figure 18a and 18b for dry and saturated sand respectively. Figure 18a shows that in dry sand the dynamic pile capacity is approximately 50% higher than the drained monotonic capacity, and that the response in the dynamic test is much stiffer. As the sample is not saturated the additional resistance cannot be due to drainage, but must reflect an inertial component of resistance.



(a)



(b)

Fig. 18. Pile performance under monotonic and snatch (dynamic) loads (a) dry sand, (b) saturated sand. Of note is the higher stiffness and capacity of the pile under snatch load due to the inertia component (after gaudin et al., 2018)

Figure 18b shows an equivalent comparison between monotonic and dynamic responses for a saturated sample (at similar relative density ~70%). In this instance the dynamic pile capacity is almost double the monotonic capacity, noting also that the monotonic capacity is lower than in the dry sample, reflecting the lower effective stress level in the saturated sample. As with the test in dry sand the pile response to dynamic loading is much stiffer than to monotonic loading, such that the pile displacements associated with these snatch loading events can be expected to be sufficiently low that the pile has sufficient residual capacity for additional operational or extreme loading events. The much higher ratio of dynamic to monotonic capacity for the saturated sample is due to the undrained response in the sand. This is to be expected, as the pile velocity reaches a maximum velocity, v = 5 m/s, such that the normalised velocity vD/c_v is 220 (with c_v ~5.10^{-4} m^2/s for sample with Dr ~ 70%).

Returning to the test result from the dry sample, Figure 19 shows that the difference between the monotonic and dynamic resistance is close to the inertial resistance, calculated as the sum of the measured pile acceleration and the pile mass. For (inviscid) dry sand the high strain rate gives no further enhancement of the capacity. The time duration of the dynamic wave load (< 10 ms) relative to the time taken for a stress wave to travel down a typical anchor pile and back (< 0.06 ms), is such that the loading is similar to that applied in a rapid load test on a pile, rather than a high energy impact test (Brown & Powell 2013). An extension of the logic used in the interpretation of the tests in dry sand is that the dynamic resistance in saturated conditions is the sum of the undrained resistance (that may include some suction at the pile base) plus an inertial component that is simply the product of the pile mass and acceleration, although there may possibly be slight viscous enhancement due to the high strain rates.

These example results not only show that a pile in sand is capable of withstanding a short duration dynamic load, of a magnitude that is considerably in excess of the monotonic capacity, but also reveal how relatively simple measurements and permutations of test conditions reveal the components of capacity that are generated during dynamic loading, allowing for the development of appropriate prediction tools.

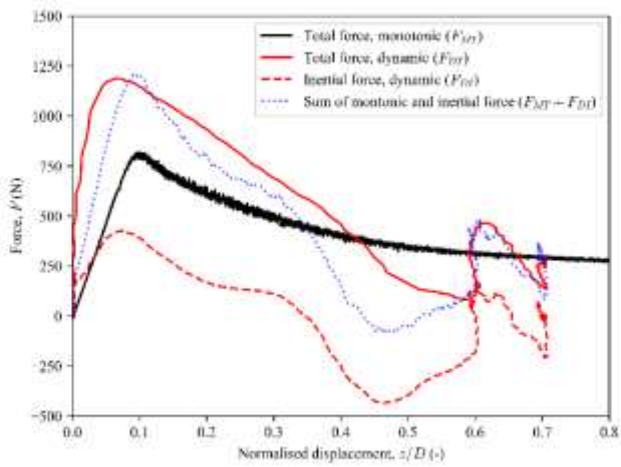


Fig. 19. Interpretation of a dynamic tensile pile test in dry sand. The inertia force is a significant component of the pile resistance under snatch load that should not be ignored in design (after Gaudin et al., 2018).

4.1 Active suction

The concept of active suction consists of pumping water from the inside of the caisson to apply an active differential pressure across the lid when the foundation is fully installed. The additional resistance due to this differential pressure increases the tensile capacity beyond that mobilised by friction at the soil-skirt interface (under drained loading). From a design point of view this potentially results in a foundation design that relies on the frictional drained capacity to withstand operational loads and on the temporary additional tensile capacity generated from passive suction to resist extreme peak events, when expected (Fiumana et al. 2017). This concept is presented in Figure 20, with respect to a typical load scenario for a point absorber wave energy converter.

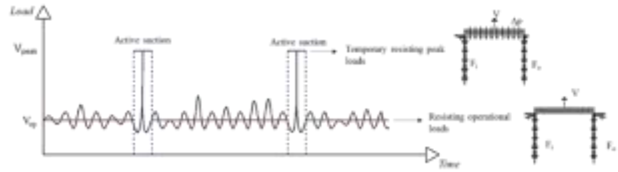


Fig. 20. Active suction concept for a suction bucked in sand. Operational loads are resisted by submerged self-weight and skirt friction, while extreme loads are resisted by added active suction pressure.

The potential for active suction to resist extreme loading has been investigated recently using reduced scale model in a centrifuge. The testing protocol involved subjecting the suction bucket to varying levels of active suction pressure and pulling it out, at a velocity that would generate drained behaviour, to assess its maximum monotonic tensile capacity, while measuring pore pressure along the internal and external side of the skirt and flow rate of active suction. This was coupled with particle image velocimetry tests on a half model to provide insights into the soil flow within and outside the suction bucket during pullout.

Figure 21 provides a summary of the test results, plotting the uplift capacity as a ratio to the drained uplift capacity, as a function of the active suction pressure applied.

Figure 21 shows that significant increase in uplift capacity can be achieved under active suction, up to a ratio of 2.1 times the drained capacity for a moderate active suction pressure of 20 kPa. Closer examinations of the pore pressures along the skirt and seepage flow indicates that this additional capacity results from the active suction pressure, the submerged weight of part of the internal plug, corrected from the upward seepage, without any degradation of the external friction along the skirt. This assumption was confirmed by PIV tests that showed most of the plug being lifted up with the bucket until peak resistance is reached, after which rapid softening occurs associated with plug liquefaction.

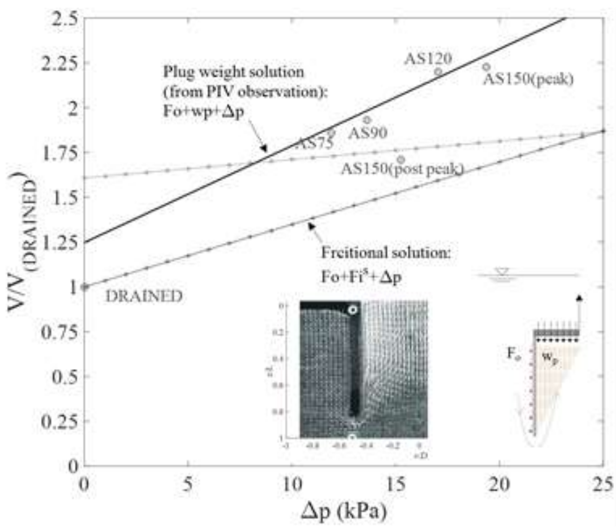


Fig. 21. Centrifuge results quantifying the increase in uplift capacity of a suction caisson upon application of active suction. The figure shows that the uplift capacity can be increased by a ratio of over 2 for moderate active suction. PIV measurements indicate a mechanism similar to that generated by passive suction, but with displacements reduced by a factor of 10.

The additional capacity generated from active suction is of the same order of magnitude than the capacity that would be generated under undrained conditions (Iskander, et al. 2002), which are likely to dominate during extreme events. In design, undrained conditions are however rarely accounted for as undrained capacity is reached at displacement that are not compatibility with serviceability conditions. The main advantage of active suction is the much stiffer response obtained, and the very small displacements needed to mobilise peak capacity, which are one order of magnitude lower than under passive suction under undrained conditions (Byrne and Houlsby, 2002).

These preliminary results are demonstrating the potential of active suction to resist extreme loading over potentially several events. Further research is being undertaken to validate these preliminary results for several episodes of cyclic loading and under real storm conditions.

5 PERSPECTIVES

Prediction of foundation response

The serviceability of an offshore wind turbine needs to be upheld over millions of load cycles over the design life. Physical evidence from recent and ongoing research provides not only a valuable database in its own right but also offers the opportunity to develop and validate predictive methods. Promising approaches have been suggested to predict the evolution of foundation stiffness and rotation accumulation. These require rigorous validation and likely refinement – a task that relies on complete sets of high quality data.

One aspect that is often overlooked but has been shown to be potentially significant is the variation in cyclic loading direction, as discussed above. This requires further research attention, with a multi-pronged approach including physical and numerical modelling.

The effect of the pore fluid response is widely acknowledged to affect soil-structure interaction even in sand, but the complexity of the load transfer is still not fully understood. Rapid shearing of saturated sand, such as under snatch loads, requires improved fundamental understanding. Numerical modelling can be a powerful tool in unlocking new insights. Apart from appropriate soil constitutive relations and contact formulation at the foundation-soil interface, this requires the coupled pore fluid-stress analysis of the foundation to either include modelling of the installation process or commence from the as-installed soil stress state. Detailed understanding of the changes in soil state due to cyclic loading - capturing the influences of the average and cyclic load magnitude, frequency, eccentricity and direction – is required to form the basis for the development of engineering recommendations.

Integrated (macro-element) modelling

Offshore wind turbine design is typically completed iteratively, with structural and geotechnical engineers using different models and exchanging loads and stiffnesses. However, the interaction between the OWT foundation and superstructure is complex, resulting in large numbers of iteration to achieve convergence. This leads to a significant number of calculations for the complete wind farm design (Kallehave et al. 2015). Integrated design has the potential to enable further optimisation, with a reduction of structural weights by up to 15% thought possible (Fischer and Vries 2011; Haghi 2012).

Macro-element models have been developed for different purposes. Some aim to predict monotonic and perhaps also cyclic loading (e.g. Salciarini et al. 2016; Jin et al. 2019), others at predicting the eigenfrequencies and ultimately the fatigue life of OWTs, hence considering corresponding low load levels and relatively few number of cycles with simulations typically taking 10-60 minutes (e.g. Page et al. 2018).

An accurate fatigue prediction is crucial for OWT design, since often the support structure design is fatigue-driven. The impact of the foundation model presented in Page et al. (2018) on the simulated overall OWT response was demonstrated by comparing integrated simulations with full-scale field data of monopile supported OWTs in the North Sea, indicating that with an appropriately calibrated foundation model it is possible to match the measured natural frequency and predict accurate fatigue loads (Page et al. 2019). An accurate fatigue prediction is crucial for the OWT design, since often the support structure design is fatigue-driven.

Integrated hydrodynamic and geotechnical engineering

Accurate determination of the OWT eigenfrequency is critical to ensure satisfactory in-service performance. However, predicting the system stiffness continues to pose challenges, largely due to difficulties in determining the operational foundation stiffness accurately over the design life of the OWT.

Scour, which lies at the interface of hydrodynamic and geotechnical engineering, can affect the stiffness and also has the potential to modify the monopile lateral capacity. Scour development around offshore structures is primarily a function of the hydrodynamics, sedimentology, and geotechnical properties at a site (Harris and Whitehouse 2012). The process is complex, environment dependent and evolves with time. In marine conditions, combined effects from currents and waves lead to variations in the equilibrium scour depth, with both erosion and backfilling occurring.

The uncertainty associated with the effects of scour on the strain dependent stiffness behaviour of the remaining soil, cyclic load response, bearing capacity and other factors potentially makes scour occurrence a critical safety issue (Prendergast et al. 2018). There is a need, therefore, to better integrate hydrodynamic and geotechnical engineering to improve prediction of scour on the basis of geotechnical information collected for offshore wind farm developments. Soil erosion testing is not yet standard (Harris and Whitehouse 2012), so it is important to develop consistent approaches and use these, together with observational data, to enhance prediction of the geotechnical performance of OWTs.

New challenges associated with emerging regions

Offshore wind is an established industry now in the North Sea, but still in its infancy in other parts of the world, although with recent strong investment in Asia and the USA. While learnings from offshore wind in the North Sea conditions will benefit development in emerging regions, their conditions pose new, individual geotechnical challenges.

Offshore wind is experiencing exponential growth in Asia in particular. Seabed sediments in this region include layered, weakly cemented and micaceous soils that may behave differently from North Sea soils. Shallow bedrock can be present, perhaps necessitating alternative foundation solutions. The development of detailed understanding and, on hence improved predictive methods, requires in depth understanding of *in situ* soils and techniques to reconstitute these soils for laboratory testing (soil element and soil-structure-interaction), such that tailor-made guidance for these regions can be developed. Further, natural hazards that are less prominent in the North Sea but need to be considered in other areas include seismicity and typhoons.

Remote floating offshore renewable energy installations

Floating renewable energy generation will play an increasing role into the future, which requires the development of anchoring solutions tailored to the specific design requirements of these devices, the seabed and loading conditions. Of further interest will be the design of remote floating offshore facilities as suitable development sites closer to shore become scarce and competition with other ocean uses increases. Such floating facilities may have multiple uses, in an effort to reduce the footprint of future developments and combine different uses to mutual benefit.

Geotechnical challenges associated with remote locations include challenging metocean conditions (potentially impacting access, weather windows for construction and maintenance, and harsh environmental loads over the operational life of the facility) and paucity of data (geophysical, geotechnical and metocean). All of these factors increase the complexity of design and optimisation and will require innovative solutions.

Field measurement data

There is significant opportunity in harnessing the rich data from instrumented offshore renewable energy installations (e.g. full datasets of operating OWTs). These can be used to improve existing prediction methods and highlight areas requiring further research. Available ocean engineering data, utilised to improve predictive models, can further guide their applicability in areas with data paucity and inform future measurement requirements.

3 CONCLUSIONS

This paper discussed (some of) the geotechnical challenges associated with offshore renewable energy installations, addressing considerations from installation and in-service performance through to survivability under extreme loading. This snapshot illustrates recent advances in response to the new challenges posed by the nature of these facilities, the environments in which offshore renewable energy is developed and the economic constraints the industry faces. Future research is anticipated to focus on integration across disciplines, to further optimize design and enable safe and reliable offshore renewable energy developments in emerging and remote areas.

ACKNOWLEDGEMENTS

This work forms part of the activities of the Centre for Offshore Foundation Systems (COFS), which is currently supported as a Centre of Excellence by the Lloyd’s Register Foundation. Lloyd’s Register Foundation helps to protect life and property by supporting engineering-related education, public engagement and the application of research. This support is gratefully acknowledged.

Many colleagues and students at COFS are involved in the research repented in this paper. This includes Prof. Fraser Bransby, Prof. Phil Watson, A/Prof. Conleth O’Loughlin, Dr Raffaele Ragni (now NGI), Dr Henning Mohr, Dr Liang Zhao, Shengsheng Fan, Nicole Fiumana, Minh-Tri Duong and the entire technical team supporting the NGCF. Their contribution is gratefully acknowledged.

REFERENCES

Andersen, K. H., Murff, J. D., Randolph, M. F., Clukey, E., Erbrich, C., Jostad, H. P., Hansen, B., Aubeny, C., Sharma, P., Supachawarote, C. (2005). Suction anchors for deepwater applications. Proceedings of international symposium on frontiers in offshore geotechnics (ISFOG) (eds S. Gourvenec and M. Cassidy), pp. 3–30. Boca Raton, FL, USA: CRC Press (Taylor & Francis).

Andersen, K.H., Jostad, H.P., Dyvik, R. (2008). Penetration resistance of offshore skirted foundations and anchors in dense sand. J. Geotech. Geoenviron. Engng, ASCE 134(1), 106–116.

Arany, L., Bhattacharya, S., Macdonald, J. H. G., Hogan, S. J. (2016). Closed form solution of Eigen frequency of monopile supported offshore wind turbines in deeper waters incorporating stiffness of substructure and SSI. *Soil Dynamics and Earthquake Engineering*, 83, 18-32.

Bienen, B., Byrne, B., Houlsby, G.T., Cassidy, M.J. (2006). Investigating six degree-of-freedom loading of shallow foundations on sand. *Géotechnique*, 56(6), 367-379, http://dx.doi.org/10.1680/geot.2006.56.6.367.

Bienen, B., Cassidy, M.J. (2006). Advances in the three-dimensional fluid-structure-soil interaction analysis of offshore jack-up structures. Marine Structures, 19(2-3), 110-140, http://dx.doi.org/10.1016/j.marstruc.2006.09.002.

Bienen, B., Klinkvort, R.T., O'Loughlin, C., Zhu, F., Byrne, B.W. (2018). Suction caissons in dense sand, Part II: Vertical cyclic loading into tension. Géotechnique, 68(11), 953–967, http://dx.doi.org/10.1680/jgeot.16.p.282.

Bienen, B., Klinkvort, R.T., O'Loughlin, C., Zhu, F., Byrne, B.W. (2018). Suction caissons in dense sand, Part I: Installation, limiting capacity and drainage. Géotechnique, 68(11), 937–952, http://dx.doi.org/10.1680/jgeot.16.p.281.

Bransby, M.F., and Randolph, M.F. (1998). Combined loading of skirted foundations. Géotechnique, 48(5): 637–655.

Brown M.J. and Powell J.M. (2013). Comparison of rapid load tests analysis techniques in clay soils. Journal of Geotechnical and Geoenvironmental Engineering. 139(1): 152-161.

Butterfield, R., and Ticof., J. (1979). Design parameters for granular soils (discussion contribution). 7th European Conf. on Soil Mechanics Foundation Engineering, 4: 259–262. British Geotechnical Society, Brighton, London.

Bye, A., Erbrich, C., Rognlien, B. & Tjelta, T. I. (1995). Geotechnical design of bucket foundation. Proceedings of the offshore technology conference, Houston, TX, USA, paper OTC 7793, pp. 869–883.

Byrne B.W., Houlsby G.T. (2002). Experimental investigation of response of suction caissons to transient vertical loading. Journal of Geotechnical and Geoenvironmental Engineering. 128(11):926-939.

Castro-Santos, L., Garcia, G.P., Estanqueiro, A., Justino, P.A.P.S. (2015). The levelized cos of energy (LCOE) of wave energy using GIS based analysis: The case study of Portugal. *Electrical Power and Energy Systems*, 65, 21-25.

Colliat, J.L., Dendani, H., Schroeder, K. (2007). Installation of suction piles at deepwater sites n Angola. *Proc. 6th Int. Conf. Offshore Site Investigation and Geotechnics Conference (SUT OSIG)*, London, UK, 413-420.

Cuéllar, P., Georgi, S., Baeβler, M., Rücker, W. (2012). On the quasi-static granular convective flow and sand densification around pile foundations under cyclic lateral loading. Granular Matter, 14, 11-25.

DNV, 2016. Support Structurs for Wind Turbines. Offshore Standard (DNVGL-st-0126).

Eide, O. & Andersen, K. H. (1984). Foundation engineering for gravity structures in the Northern North Sea, publication no. 154. Oslo, Norway: Norwegian Geotechnical Institute.

Erbrich, C.T., Tjelta, T.I. (1999). Installation of Bucket Foundations and Suction Caissons in Sand – Geotechnical Performance. Proc. Offshore Technology Conference, Houston, USA, OTC10990.

Fan, S. (2019). *Effect of installation on the subsequent response of offshore monopiles under lateral loading*. Forthcoming PhD Thesis, University of Western Australia.

Fievez J., Sawyer T., "Lessons learned from building and operating a grid connected wave energy plant", in 11th European Wave and Tidal Energy Conference, Nantes, 2015.

Fischer, T., de Vries, W. (2011) *Final report 4.1: Integration of support structure and wind turbine design*. Upwind Project Report, Universität Stuttgart, Stuttgart.

Fiumana, N., Gaudin, C., Tian, Y. (2017). Active Suction Anchors for Floating Renewable Energy. Proc. 12th European Wave and Tidal Energy Conference.

Fiumana, N., Bienen, B., Govoni, S., Gourvenec, S., Cassidy, M.J., Gottardi, G. (2019). Combined loading capacity of skirted circular foundations in loose sand. *Ocean Engineering*, 183, 57-72, https://doi.org/10.1016/j.oceaneng.2019.04.095.

Galavi, V., Beuth,L., Zuada Coelho, B., Tehrani, F.S., Hölscher, P. van Tol, F. (2017). Numerical simulation of pile installation in saturated sand using material point method. 1st International Conference on the Material Point Method (MPM 2017), Procedia Engineering 175, 72-79.

Gaudin C., O'Loughlin C.D., Bienen B. (2018). Geotechnical modelling for offshore renewables. Proceedings of the 9th International Conference on Physical Modelling in Geotechnics, London, UK. 33-42.

Gottardi, G., Houlsby, G.T., and Butterfield, R. (1999). Plastic response of circular footings on sand under general planar loading. Géotechnique, 49(4): 453–469.

Gottardi, G., Govoni, L., and Butterfield, R. (2005). Yield loci for shallow foundations by "swipe" testing. Frontiers in Offshore Geotechnics, ISFOG 2005 - Proceedings of the 1st International Symposium on Frontiers in Offshore Geotechnics.

Gourvenec, S., and Randolph, M. (2003). Effect of strength non-homogeneity on the shape of failure envelopes for combined loading of strip and circular foundations on clay. Géotechnique, 53(6): 575–586.

Haghi R. 2012 Integrated design and optimisation of an offshore wind turbine monopile support structure. Proc. 4th Scientific Conf. on the Science of Making Torque from Wind, Oldenburg, Germany.

Hansen, B., Nowacki, F., Skomedal, E. & Hermstad, J. (1992). Foundation design: Troll platform. In Behaviour of offshore structures: proceedings of the sixth international conference 1992 (BOSS '92) (eds M. H. Patel and R. Gibbins), 921–936. London, UK: BPP Technical Services Ltd.

Harris, J.M., Whitehouse, R.J.S. (20) Scour development around large-diameter monopiles in cohesive soils: evidence from the field. *Journal of Waterway, Port, Coastal, and Ocean Engineering (ASCE)*, https://doi.org/10.1061/(ASCE)WW.1943-5460.0000414.

Heins, E., Grabe, J. (2017). Class-A-prediction of lateral pile deformation with respect to vibratory and impact pile driving. Computers and Geotechnics, 86, 108-119.

Henke, S., Bienen, B. (2013). Centrifuge tests investigating the influence of pile cross-section on pile driving resistance of open-ended piles. International Journal of Physical Modelling in Geotechnics, 13(2), 50-62, http://dx.doi.org/10.1680/ijpmg.12.00012.

Houlsby, G.T. (2016). Interactions in offshore foundation design. *Géotechnique*, 66(10), 791-825 http://dx.doi.org/10.1680/jgeot.15.RL.001.

Houlsby, G.T., and Cassidy, M.J. (2002). A plasticity model for the behaviour of footings on sand under combined loading. Géotechnique, 52(2): 117–129.

Houlsby, G.T., Byrne, B.W. (2005). Calculation procedures for installation of suction caissons in sand. Proc. Instn Civ. Engrs – Geotech. Engng 158(3), 135–144.

Iskander M., El-Gharbawy S., Olson R. (2002). Performance of suction caissons in sand and clay. Canadian geotechnical Journal, 39: 576-584.

Kallehave, D., Byrne, B.W., LeBlanc Thilsted, C., Kousgaard Mikkelsen, K. (2015) Optimisation of monopiles for offshore wind turbines. *Phil. Trans. Roy. Soc.* A 373 20140100, http://dx.doi.org/10.1098/rsta.2014.0100.

Klotz, E.U., Coop, M.R. (2001). An investigation of the effect of soil state on the capacity of driven piles in sand. *Géotechnique*, 51(9), 733-751.

Ko, J. Yeong, S., Lee, J.K. (2016). Large deformation FE analysis of driven steel pipe piles with soil Plugging. Computers and Geotechnics, 71, 82-97.

LeBlanc, C., Byrne, B.W., Houlsby, G.T. (2010a). Response of stiff piles to random two-way lateral loading. *Géotechnique*, 60(9), 715-721.

LeBlanc, C., Houlsby, G.T., Byrne, B.W. (2010b). Response of stiff piles in sand to long-term cyclic lateral loading. Géotechnique, 60(2), 79-90.

Levy, N., Einav, I. and Randolph, M.F. (2007). Effect of recent load history on laterally loaded piles in normally consolidated clay. *Int. J. for Geomechanics*, ASCE, 7(4), 277-286.

Lovera, A., Ghabezloo, S., Sulem, J., Randolph, M.F., Kham, M. and Palix, E. (2019). Effects of a multi-directional loading sequence on offshore wind turbine natural frequencies. *Proc. 17th European Conf. on Soil Mechanics and Geotechnical Engineering*, Reykjavik.

Martin, C.M, Houlsby, G.T. (2000). Combined loading of spudcan foundations on clay: laboratory tests. *Géotechnique*, 50(4), 325-338.

McCarron, W.O. (2015). Bounding surface model for soil resistance to planar cyclic lateral pile displacements. *Computers and Geotechnics*, 65, 285-290.

McCarron, W.O. (2016). Bounding surface model for soil resistance to cyclic lateral pile displacements with arbitrary direction. *Computers and Geotechnics*, 71, 47-55.

Nanda, S., Arthur, I., Sivakumar, V., Donohue, S., Bradshaw, A., Keltai, R., Gavin, K., Mackinnon, P., Rankin, B., Glynn, D. (2017). Monopiles subjected to uni- and multi-lateral cyclic loading. Geotechnical Engineering, http://dx.doi.org/10.1680/jgeen.16.00110.

Neary, V.S., Previsic, M., Jepsen, R.A., Lawson, M.J., Yu, Y.H., Copping, A.E., Fontaine, A.A., Hallett, K.C. (2014). *Methodology for Design and Economic Analysis of Marine Energy Conversion (MEC) Technologies*.

Nicolai, G., Ibsen, L.B., O'Loughlin, C.D., White, D.J. (2017). Quantifying the increase in lateral capacity of monopiles in sand due to cyclic loading. Géotechnique Letters 7, 1–8, http://dx.doi.org/10.1680/jgele.16.00187.

Nova, R., and Montrasio, L. (1991). "Settlements of shallow foundations on sand." Géotechnique, 41(2): 243–256.

Page, A.M., Grimstad, G., Eiksund, G.R., Jostad, H.P. (2018). A macro-element pile foundation model for integrated analyses of monopile-based offshore wind turbines. *Ocean Engineering*, 167, 23-35.

Page, A.M., Næss, V., De Vaal, J.B., Eiksund, G.R., Nygaard, T.A. (2019). Impact of foundation modelling in offshore wind turbines: comparison between simulations and field data. *Marine Structures*, 64, 379-400.

Phuong, N.T.V., van Tol, A.F., Elkadi, A.S.K., Rohe, A. (2016). Numerical investigation of pile installation effects in sand using material point method, Computers and Geotechnics, 73, 58-71.PhysOrg (2016). www.phys.org/news/2016-09-wave-produced-electricity-online-hawaii.html

Prendergast, L.J., Reale, C., Gavin, K. (2018). Probabilistic examination of the change in eigenfrequencies of an offshore wind turbine under progressive scour incorporating soil spatial variability. *Marine Structures*, 57, 87-104.

Ragni, R., Bienen, B., Stanier, S., O'Loughlin, C., Cassidy, M.J. (2019). Observations during suction bucket installation in sand. International Journal of Physical Modelling in Geotechnics, https://doi.org/10.1680/jphmg.18.00071.

Roscoe, K.H., and Schofield, A.N. (1956). The stability of short pier foundations in sand. British Welding Journal, 3(8): 343–354.

Rudolph, C. (2014). Untersuchungen zur Drift von pfählen unter zyklischer, lateraler last aus veränderlicher Richtung. PhD Thesis, Technische Universität Hamburg-Harburg (TUHH), Germany.

Rudolph, C., Bienen, B., Grabe, J. (2014). Effect of variation of the loading direction on the displacement accumulation of large diameter piles under cyclic lateral loading in sand. Canadian Geotechnical Journal, 51(10), 1196-1206, http://dx.doi.org/10.1139/cgj-2013-0438.

Salencon, J., and Pecker, A. (1995). Ultimate bearing capacity of shallow foundations under inclined and eccentric loads, Part I, Purely cohesive soil. Eur. J. Mech. A/solids, 14(3): 349–375.

Senders, M., Gaudin, C., Randolph, M.F. (2007). Theory for the installation of suction caissons in sand overlaid by clay. Proc. 6th International Offshore Site Investigation and Geotechnics Conference: Confronting New Challenges and Sharing Knowledge, London, UK, 429-438.

Senders, M., Randolph, M.F. (2009). CPT-based method for the installation of suction caissons in sand. J. Geotech. Geoenviron. Engng, ASCE 135(1), 14-25.

Stapelfeldt, M., Bienen, B., Grabe, J. (2018). Centrifuge tests investigating the effect of suction caisson installation in dense sand on the state of the soil plug. *Proc. 9th International Conference on Physical Modelling in Geotechnics (ICPMG 2018)*, London, UK, 1, 669-674.

Stapelfeldt, M., Bienen, B., Grabe, J. (2019). The influence of the drainage regime on the installation and the response to vertical cyclic loading of suction caissons in dense sand. Ocean Engineering, under review.

Sturm, H. (2017). Design Aspects of Suction Caissons for Offshore Wind Turbine Foundations. Proc. 19th ICSMGE – Seoul, TC209 workshop, 45-63

Su. D. (2011). Resistance of Short, Stiff Piles to Multidirectional Lateral Loadings. Geotechnical Testing Journal, 35(2), 313-329.

Tjelta, T. I. (2015). The suction foundation technology. In Frontiers in offshore geotechnics (ISFOG) III (ed. V. Meyer), pp. 85–93. Boca Raton, FL, USA: CRC Press (Taylor & Francis).

Tjelta, T. I., Guttormsen, T. R. & Hermstad, J. (1986).Large-scale penetration test at a deepwater site. Proceedings of the offshore technology conference, Houston, TX, USA, paper OTC 5103.

Watson P.G., Gaudin C., Senders M., Randolph M.F. (2006). Installation of suction caisson in layered soil. Proceedings of the 6th International Conference on Physical Modelling in Geotechnics, Hong-Kong. 1: 685-692.

Weller S.D., Johanning L., (2014). Specific requirements for marine renewable energy foundation analysis, Deliverable 4.2 of the DTOcean project.

Wichtmann, T., Triantafyllidis, T. (2016a). An experimental data base for the development, calibration and verification of constitutive models for sand with focus to cyclic loading. Part I: tests with monotonic loading and stress cycles. Acta Geotechnica, 11(4), 739-761.

Wichtmann, T., Triantafyllidis, T. (2016b). An experimental data base for the development, calibration and verification of constitutive models for sand with focus to cyclic loading. Part II: tests with strain cycles and combined loading. Acta Geotechnica, 11(4), 763-774.

Wichtmann, T., Triantafyllidis, T. (2019). On the influence of multiple polarization changes on the cumulative deformations in sand under drained high-cyclic loading. Geotechnical Testing Journal, 43. https://doi.org/10.1520/GTJ20170298.

Wind Power Offshore (2019). https://www.windpoweroffshore.com/article/1525362/europes-offshore-wind-costs-falling-steeply.

World Wind Energy Association (WWEA). (2019). https://wwindea.org/blog/2019/02/25/wind-power-capacity-worldwide-reaches-600-gw-539-gw-added-in-2018/

Zhang, Y., Bienen, B., Cassidy, M.J. (2014). Jack-up push-over analyses featuring a new force resultant model for spudcans in soft clay. Ocean Engineering, 81, 139-149, http://dx.doi.org/10.1016/j.oceaneng.2014.02.008.

Zhao L., Bransby F., Gaudin C., Cassidy M.J. (2019). Capacity of caissons in dense sand under inclined loading. Journal of Geotechnical and Geoenvironmental Engineering. (under review).

Zhu, F., Bienen, B., O'Loughlin, C.D., Cassidy, M.J., Morgan, N., (2018a). Suction bucket foundations for offshore wind energy: cyclic response in sand and layered soils. Géotechnique, https://doi.org/10.1680/jgeot.17.P.273.

Zhu, F., Bienen, B., O'Loughlin, C., Morgan, N., Cassidy, M.J. (2018b). The response of suction caissons to multidirectional lateral cyclic loading in sand over clay. Ocean Engineering, 170, 43-54, https://doi.org/10.1016/j.oceaneng.2018.09.005.

Zhu, B., Byrne, B.W., Houlsby, G.T. (2013). Long-term lateral cyclic response of suction caisson foundations in sand. J. Geotech. Geoenviron. Engng, 139(1), 73-83.