A LIFETIME OF OFFSHORE GEOTECHNICS - CAREER REFLECTIONS AND LESSONS LEARNED

Mark F. Randolph, University of Western Australia, Perth, Australia, mark.randolph@uwa.edu.au

ABSTRACT

This is a rather unusual invited paper, written in the first person with a mix of personal anecdote and technical aspects. In preparing it, I have enjoyed the opportunity for reflection, but suspect that the lessons learned may well prove a disappointment! As an academic, I have become largely immune to the grandiose claims of most grant applications, where goals often prove elusive; as a consultant, I am constantly reminded of persisting gaps in our knowledge, and the need to rely on potentially inferior design solutions that have stood the test of time, even though recent approaches based more closely on the physics of the problem might appear superior. I will present examples of these in the paper, and also muse on the drivers that eventually overcome inertia in our design practice.

Keywords: design, geotechnical, guidelines, offshore, practice, research

INTRODUCTION

When I received an invitation to deliver a keynote lecture "*reflecting on my career in offshore geotechnics*", my first reaction was that it was a bit premature, even rude(!), as I was still very much in harness. However, I have since decided to take the hint and duly retired, or at least ceased to draw a salary, from the University of Western Australia from 30 June 2020. In truth, though, I was most honoured by the invitation and would like to express my sincere appreciation to the organising committee of ISFOG 2020 for the opportunity to reflect on how the offshore industry, and geotechnical design in particular, has evolved over the last 30 plus years.

I will start with some details of my own transition into offshore practice and then review in turn aspects of deep (piled) and shallow foundations, and the range of anchoring solutions that were developed as the industry moved to deep water. In particular I will reflect on issues that have been pivotal in encouraging changes in design approaches. I will also interleave aspects of offshore developments in Australia, where the carbonate seabed sediments have necessitated special approaches.

EARLY CAREER

I completed my doctoral studies towards the end of 1977, focusing on elastic interaction between piles and soil. Although generic in nature, the solutions developed have found rather greater application in onshore practice – in particular with respect to my pile group analysis software, PIGLET – than for offshore design. My initial involvement in offshore geotechnics followed soon after, courtesy of my supervisor, Peter Wroth, in the form of a joint industry research project, ESACC (effective stress axial capacity in clay). This was administered by Amoco Production Company, based in Tulsa (another eye-opener for me!), which was my first contact with the often flamboyant, but troubled, Ben Murphy. The worthy (though ultimately only partially attained) goal was to use an effective stress approach to track changes in stress states in the immediate vicinity of open-ended driven piles, and thereby develop an improved design approach for the time-dependent axial capacity.

Of course much was indeed learned in the ESACC project. Cavity expansion analogues were used as the basis for estimating stress changes and excess pore pressure distributions resulting from pile installation, and these allowed sensible analysis of the time scale of consolidation around driven piles and hence of the developing frictional capacity (e.g. as summarised in Randolph 2013). Different effective stress methods that emanated from the project were summarised by Lee Kraft (Kraft 1982). However, the understanding gleaned from the project also led, perhaps indirectly, to my OTC paper with Ben Murphy (Randolph and Murphy 1985) that, rightly or wrongly, has since formed the basis of the API (2011) and ISO (2016) guidelines for axial pile capacity. Caveats on the design method, in particular with respect to low plasticity index silts, are provided in the guideline commentaries. Like many parts of the guidelines, the method is overdue for replacement by a more scientific approach, perhaps linked to field penetrometer data (e.g. as proposed by Jardine et al. 2005), although the logic for linking to penetrometer data is much weaker for sediments where pile installation is essentially undrained than for the case of sands where installation is drained. Overall, without compelling evidence of unconservativism (or costly excessive conservativism), an updated of the current method for driven piles in clay has yet to rise up the priority list.

Given the location of this conference it is apposite to recall that my first visit to the US, in 1978 immediately post-PhD, was to UT Austin to 'sit at the feet' of Lymon Reese – also at the instigation of Peter Wroth, who made the introduction. I have fond memories of the visit, though I suspect I was the only person lounging on the grass at Barton Springs working my way through a stack of half a dozen PhD theses from Lymon's students. I suspect I may also have disgraced myself at his golf club (in the height of summer), downing cold beer at much the same rate as Lymon was drinking iced tea.

During the early 1980s I also had my first contact with Don Murff, then at Exxon, who has remained a close friend and colleague ever since, holding each other in mutual and high regard. For my part, the more I searched the literature, the more I found (retrospectively) that Don had published similar, but often better, solutions to those I thought I had developed, and it was Don who pointed out the error in my (in the sense of accepting responsibility for the error!) upper bound solution for a cylinder moving laterally through soil (Randolph and Houlsby 1984). Through him, and with the support of Ben Murphy (then Chair), I was invited to join the API Geotechnical Resources Group in 1985, where for many years (until the committee merged with the corresponding ISO committee in 1998) I was the only academic. By this quirk, and well after migrating to Australia, I retained my right to vote on guidelines directed specifically towards offshore foundations in the Gulf of Mexico.

I learned a lot during my early years on the API Geotechnical Resources Group, quite apart from broadening my technical experience. Full of youthful exuberance to replace (in my view) questionable design approaches by improved fundamentally scientific calculation methods, more experienced colleagues such as Don Murff exemplified more restrained, and highly effective, contributions that prioritised aspects considered unfit for purpose. It took me a few years to really understand how such guideline committees work, with the deliberate measured pace of change and the need to assess carefully how any change would affect design calculations.

I was fortunate in my final two years (1985-6) at Cambridge to lead a centrifuge modelling project aimed at deriving an improved design approach for lateral pile response in carbonate sediments. This work was for Exxon (through Esso Australia) to underpin the design of a strut-strengthening system for the first-generation platforms in Bass Strait. To be effective, the system required accurate assessment of the lateral pile stiffness, for which it was felt that the Reese p-y curves for sand might not be applicable to the more compressible carbonate sediments around Australia. The model tests were validated by small piles tested in a pit of reconstituted carbonate material, and the resulting p-y curves were expressed as power law functions of depth z and lateral displacement y - see later discussion (Wesselink et al. 1988).

There is nothing like a failure to stimulate change, and so it proved with the driven pile foundations for North Rankin A, the first major oil and gas platform on Australia's North West Shelf. The piles largely free fell (at frightening speeds) until reaching competent cemented calcareous sediments at just over 100 m depth below mudline. At the time (1984) I consulted on this project with BP (one of the NWS partners) in the UK, through McClelland Engineers prior to their merging with Fugro, and also visited Perth a couple of times to work with the operator Woodside. This led indirectly to the life-changing decision for myself and my family to migrate to Perth, where I joined the University of Western Australia as a Senior Lecturer. The move caused considerable surprise among my UK colleagues, essentially revoking a tenured position at a leading university there for a relatively modest position in the colonies! However, perhaps influenced by the somewhat misogynistic attitudes prevalent in Cambridge at the time, we took the view that the worst that might happen was spending a few years in a beautiful setting and climate. On the more positive side, the NWS seemed set to burgeon, and Woodside, then represented by Mohamed Khorshid, appeared keen to collaborate with UWA to develop local expertise in foundation design in carbonate sediments.

In spite of geographical challenges, I continued to serve on the API Geotechnical Resources Group, endeavouring to attend at least one meeting each year – generally at OTC. In that way, and also by dint of a three-month industry sabbatical in 1993, spent in the offices of the newly merged Fugro-McClelland Marine Geosciences in Houston, where I was hosted by Rathindra Dutt, I managed to retain my connections with the US-based oil and gas industry and design practice in the Gulf of Mexico. I will return later to offshore developments in Australia, but will turn now to some of the technical developments in which I have had some involvement over the last thirty years.

PILE FOUNDATIONS

Axial shaft resistance in sand

While axial pile design in clay has remained relatively static, significant investment in developing improved approaches for axial capacity in free-draining (sandy) sediments was made immediately prior to the first ISFOG in 2005 (Clausen et al. 2005; Jardine et al. 2005; Kolk et al. 2005; Lehane et al. 2005). All of the approaches developed were based on the cone resistance q_c, which may be considered to provide a superior measure of strength than other approaches, avoiding reliance on a single friction angle linked to broad descriptions of relative density, ignoring the known influence of effective stress level. In addition, and critically, the methods capture the effects of friction degradation, whereby the ratio of shaft friction to cone resistance at a given depth decreases as a function of the length of pile driven past that location (Lehane et al. 1993; Alm and Hamre 2001). The methods also give due consideration to the area ratio A_r of the pile (ratio of steel area to gross area), which affects the magnitude of normal effective stress, relative to the cone resistance, that is developed near the pile tip.

Estimation of limiting shaft friction τ_s from the Lehane et al. (2005) approach may be expressed as

$$\frac{\tau_s}{q_c} = 0.021 A_r^{0.3} \left[\max\left(\frac{h}{2D}, 1 \right) \right]^{-0.5} f_{ct} \tan \delta \qquad [1]$$

The other methods are essentially similar but with small variations in the various coefficients. The maximum normal effective stress estimated to act over the bottom (in this case) two diameters of the pile, as expressed by the coefficient before the square bracketed term, ranges between about 2% for a solid pile down to 1% for an area ratio of 0.1 (a pile diameter to wall thickness ratio of about 40). The inverse square root degradation law then halves this by a distance of eight diameters from the pile tip etc.

This type of approach therefore captures effectively observations made of actual pile capacity in sand (e.g. Vesic 1977), whereby driving additional pile length may erode shaft capacity in the upper part of the pile faster than it is developed near the tip. It is radically different from the classical approach that has persisted in the main text of the API-ISO guidelines, which results in linearly increasing shaft friction profiles (proportional to the vertical effective stress) until the specified limiting values are reached. In the 15 years that have passed since their introduction into the API-ISO guidelines, the CPT-base methods have stood the test of time well and their mainstream acceptance is now overdue. So, it is very timely to see the new ‘unified’ approach presented at this conference (Lehane et al. 2020, Nadim et al. 2020); I gather there are plans to integrate it promptly as the main text method for axial pile capacity in sand, with the current classical approach relegated to the commentary, or just to a distant memory.

Lateral response

Most design analysis for the lateral response of piles is conducted using a 1-D beam column model of the pile together with non-linear p-y curves to capture layer by layer pile-soil interaction. In sands, it would seem logical to link p-y curves more directly with the cone resistance, albeit with some possible adjustments at shallow depth, given the relative sizes of pile and cone. Essentially, this was the approach derived by Wesselink et al. (1988) from centrifuge and small scale prototype pile tests in carbonated sediments. The p-y curves were expressed (in non-dimensionalised form) as

$$\frac{p}{\gamma' D^2} = R\left(\frac{z}{z_0}\right)^n \left(\frac{y}{D}\right)^\gamma \qquad [2]$$

where z_0 was a reference length of 1 m and the three coefficients were optimised as R = 650-850 kPa, n = 0.7 and γ = 0.65. Cone tests through the reconstituted sand showed cone resistance proportional to depth, so the depth term above is essentially the cone resistance.

This form of p-y curve was later validated further by Dyson and Randolph (2001) (substituting $q_c/\gamma' D$ for z/z_0), with n = 0.72 and γ = 0.58. A slight variation was also proposed by Novello (1999), who incorporated an additional term $(z/D)^{1-n}$ on the righthand side, together with powers of n = 0.67 and γ = 0.5. More recently, the approach was applied to piles in silica sand by Suryasentana and Lehane (2014) in the form

$$\frac{p}{\gamma' z D} = C\left(\frac{q_c}{\gamma' z}\right)^n \left(\frac{y}{D}\right)^\gamma \quad \text{or} \quad \frac{p}{\gamma' D^2} = C\left(\frac{z}{D}\right)^{1-n} \left(\frac{q_c}{\gamma' D}\right)^n \left(\frac{y}{D}\right)^\gamma \qquad [3]$$

This is essentially similar to the Novello (1999) formulation, with recommended parameters of C = 4.2, n = 0.68 and γ = 0.56. The paper also presents a slightly modified version that includes a cut-off limiting lateral resistance, although it is not clear that this is needed for most design.

Although no doubt there will be some debate in the choice of the various coefficients in Eq. [3], it would seem appropriate to introduce this type of approach, initially as an alternative method, in the API-ISO guidelines, consistent with the general philosophy that penetrometer tests provide the most robust measure of the in situ strength of sand.

Drivers for change

The incentive for the CPT-based methods discussed above has been mainly to capture the underlying physics better, while at the same time reducing potential unconservatism in traditional approaches. However, economic considerations (though also linked to improved safety) are currently adding pressure for revision of lateral pile design across a range of soil types. Key applications are (a) risers, specifically vertical well conductors; and (b) monopiles supporting offshore wind turbines. In both cases, design hinges more on serviceability criteria – respectively fatigue for risers, stiffness and cumulative deformations for monopiles – rather than ultimate limit states.

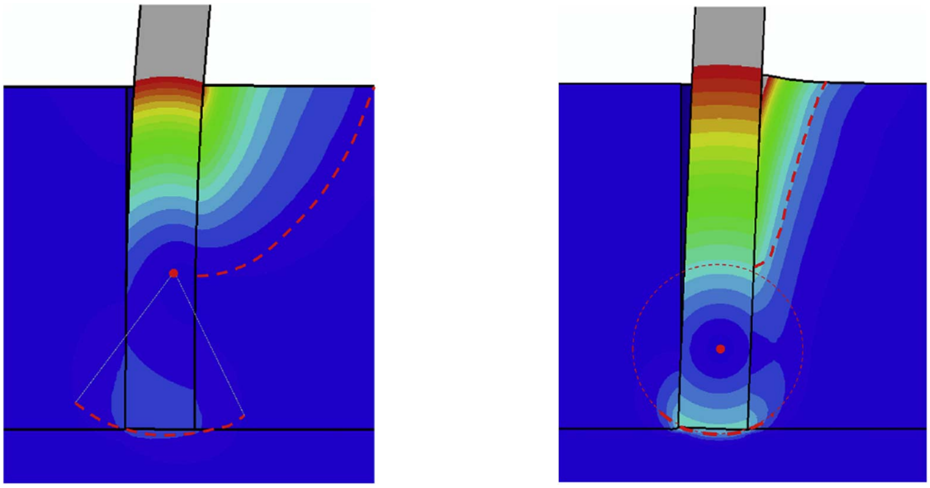
Combined physical and numerical modelling studies of the response of long conductors (essentially similar to laterally loaded piles) have led to a series of papers indicating significant underprediction of the small-displacement stiffness using the classical API p-y curves for clay (Jeanjean 2009; Zakeri et al. 2015). Jeanjean proposed a modified load transfer curve for monotonic loading, in the form

$$\frac{p}{p_{\max}} = \tanh\left[\frac{G_{\max}}{100 s_u}\left(\frac{y}{D}\right)^{0.5}\right] \le f\,\frac{G_{\max}}{p_{\max}}\,y \qquad [4]$$

where I have added an overriding limit on the stiffness (which otherwise would tend to infinity as y approaches zero), with f typically taken in the range 4-5. Both the Jeanjean and Zakeri et al. studies paid considerable attention to modelling the evolving stiffness for small displacement cycles, accurate quantification of which is vital for fatigue analysis.

For monopile design, small displacement stiffness is also vital, as this influences the natural frequency of the complete structure. Field measurements have shown that conventional load transfer approaches have tended to underestimate natural frequencies (Kallehave et al. 2015), resulting in a risk of impinging on the blade passing frequency. Another aspect of monopile design is their relatively low embedment, typically 3-6 times the diameter, and the high moment loading ratio *M*/*HD* (reflecting the eccentricity ratio from the wind and wave loading, noting that monopiles are essentially free-headed, as opposed to the rotational restraint provided by a jacket structure). This requires more sophisticated load transfer modelling, including base shear and moment springs and also moment-rotation m-θ springs distributed down the pile shaft. The joint industry PISA project has resulted in detailed recommendations for evaluating load transfer curves for monotonic loading conditions, so far for stiff clay (Byrne et al. 2020) and dense sand (Burd et al. 2020).

While the PISA recommendations were quite specific for the two soil types considered, more generic recommendations for monopiles in soft clay have been proposed by Zhang and Andersen (2019). The recommendations emanate from finite element analyses with a general non-linear stress strain model, following the concept of 'morphing' the stress-strain model to the resulting non-linear *p*-*y* curves (and corresponding curves for the pile base) by appropriate scaling. The snapshots of displacement patterns reproduced in Fig. 1 (for a monopile with L/D = 5) illustrate nicely the transition from a relatively flexible pile response at low loads, with very little deformation reaching the pile tip, to the 'rigid body' ultimate failure mechanism, which is essentially identical to that for suction caissons under high moment loading (e.g. Randolph et al. 2020).



(a) Small displacement (y_m/D = 0.2%) (b) Large displacement (y_m/D = 31%)

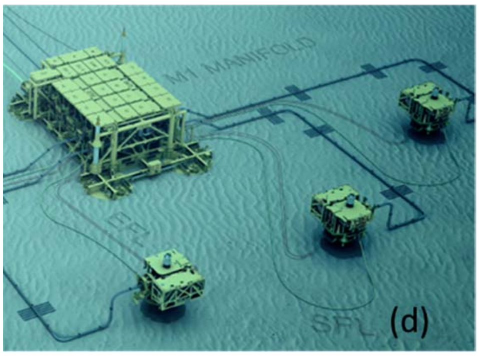
Fig. 1. Soil displacement patterns for monopile (after Zhang and Andersen 2019)

The various recommendations for new load transfer curves for application to monopile design will no doubt work their way gradually into design codes, they may also eventually have application for longer piles as used for offshore jacket structures. My key point here, though, are the drivers that have led to re-assessment of load transfer curves that have, till now, remained largely unchanged for several decades. The relatively young offshore wind industry, where the foundations represent a much greater proportion of the overall development cost than is typical for oil and gas facilities, has provided the main impetus. A somewhat similar impetus for innovation occurred in the oil and gas industry around the turn of this century, with the evolution from fixed platforms in shallow to moderate water depths, to floating structures in water depths exceeding several hundred metres. The effects of this on shallow foundation design and the rapid proliferation of anchoring systems are discussed in the following sections.

SHALLOW FOUNDATION SYSTEMS FOR DEEP WATER

Stability

For deep water developments, the focus for shallow foundation design switched from the massive gravity-based Condeep structures of the North Sea, such as Brent B, Troll and Gullfaks C (Andersen et al. 2008), to the myriad subsea structures that are needed for typical deep water facilities (e.g. Fig. 2a). The range from relatively large and heavy manifold structures to small well-head and pipeline end termination (PLET) mudmats. gives an indication of the size of the manifolds and foundation systems. At the upper end, Fig. 2b shows the manifolds for the Jansz field, in around 1200 m water depth off Australia's north-west shelf, with a foundation of around 40 m × 30 m in plan with skirts of 3 m, designed to support a manifold weighing over 900 tonnes in air (Broadway and Tachoires 2016). The net bearing pressure to be sustained, although not high, needs to be considered in the light of the shear strength profile, with average strengths over the upper 10 m of around 15 kPa and very low mudline strengths prior to any consolidation under the foundation loading. However, unlike massive gravity-based structures, the more critical loading is lateral (including moments and torsion), while the relatively constant vertical component might represent only 20-30% of the vertical bearing capacity.



(a) Schematic of Gorgon subsea manifolds (Watson et al. 2019)

(b) Jansz manifolds during load out (Broadway and Tachoires 2016)

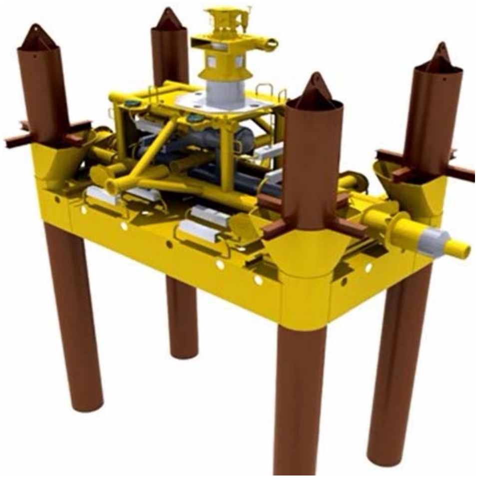
Fig. 2 Subsea layout and Jansz manifolds for Greater Gorgon development

The lateral loading on subsea structures arises partly from bottom currents, but more importantly from the connected pipe infrastructure, including initial loads arising during connection of slightly mis-aligned flanges and in-service loads from temperature and pressure induced expansion and contraction of the flowlines and spools. The combination results in complex six degree of freedom load cases that have led to innovative design approaches, and also instigated yield envelope design approaches within the more recent API and ISO guidelines. Although at present these are viewed as 'alternative' to the main text approaches, they would appear more suitable for foundations where the mode of failure is more that of sliding and overturning, rather than classical bearing failure.

The complexity of the loading for subsea foundations, and the pressure to minimise the size (in terms of weight and footprint) in order to facilitate installation, has led to various design innovations. These include synthesis of extensive 3-D numerical analyses in order to allow the design loading to be compared with a collapsed 2-D yield envelope (Feng et al. 2014; 2015), and also innovative approaches such as incorporating corner pin-piles in so-called hybrid mudmats to increase the sliding resistance (Demel et al. 2016; Won et al. 2018). A design basis for the latter was developed through a combination of centrifuge model testing and numerical analysis (Gaudin et al. 2012; Dimmock et al. 2013).

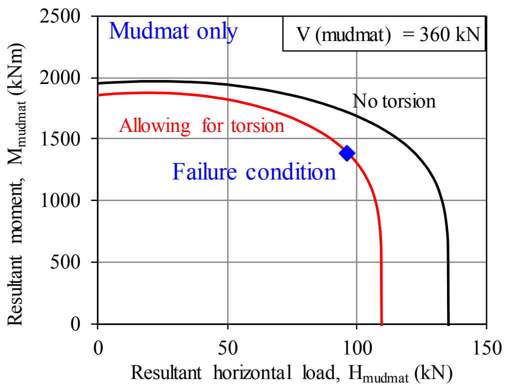
An example of a hybrid foundation is shown in Fig. 3 (Demel et al. 2016). In this case the mudmat was some 5 m by 8.8 m in plan, with the 1 m diameter piles to be embedded a minimum of 7 m in order to satisfy design criteria on ultimate capacity. In the original design approach of Dimmock et al. (2013), the piles were assumed to carry the entire sliding and torsional loading, the mudmat would carry the submerged weight of the structure and moments were shared between piles and mudmat. A more sophisticated design approach is to allow the proportions of each type of loading (vertical, sliding (and torsion) and moment) to be varied between mudmat and piles, such that both components of the foundation reach their limiting capacity under the design load. This is illustrated for a hypothetical example in Fig. 4, which shows the final design loads plotted with respect to the torsion-adjusted yield envelopes for each foundation component. In this case, the mudmat carries about 75% of the vertical load, the piles carry about 80% of the sliding loads (horizontal and torsion), while both components carry similar proportions of the resultant moment.

(a) In-line mudmat – as laid

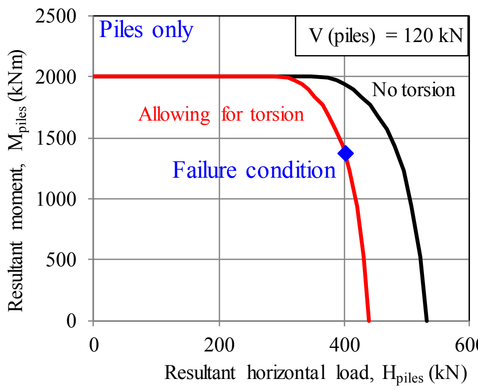


(b) Final mudmat with pin-piles

Fig. 3 Example hybrid subsea foundation (courtesy Subsea 7)



(a) M-H yield envelopes for mudmat



(b) M-H yield envelopes for piles

Fig. 4 Optimised design solution for a hybrid subsea foundation

Initial sizing of subsea foundations is often carried out based on the in situ shear strength profile. In reality, however, the shear strengths will change under the effects of (a) consolidation under the submerged weight of the foundation and infrastructure it carries, and (b) the effects of cyclic loading. These two influences compensate each other, at least to some extent, but both need to be taken into account in the final design. Relatively simple approaches have been published in recent years for the increase in vertical, horizontal and moment capacity arising from consolidation under different proportions of the original bearing capacity (Gourvenec et al. 2014; Feng and Gourvenec 2015; Vulpe et al. 2016), with an example shown in Fig. 5. The increase in capacity can be significant, even where the self-weight preloading is only 20-30% of the undrained vertical bearing capacity.

Allowance for reduction in shear strength under cyclic loading is more challenging, requiring assessment of mean and cyclic changes in shear stress throughout the relevant soil domain that might be involved in any failure. A number of factors affect the cyclic shear strength, including strain-rate effects, which lead to increased ultimate values compared with a conventional slow monotonic test, stress path, with different cyclic strength reduction depending on the intermediate principal stress, numbers of cycles and design strain levels (Andersen 2015). Ideally, project-specific design charts or algebraic relationships should be developed for any given soil type. In practice, however, a common approach is to use existing charts and calibrate them, with minor adjustments as needed, for the sediments in question.

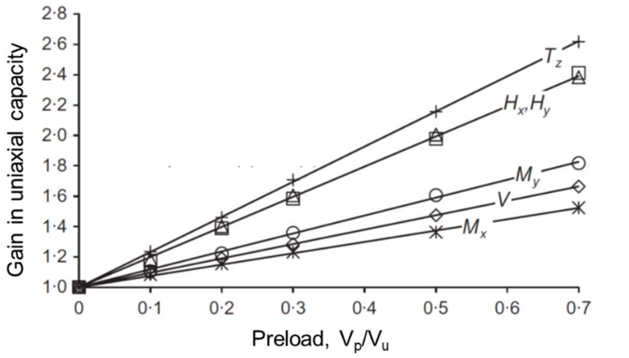
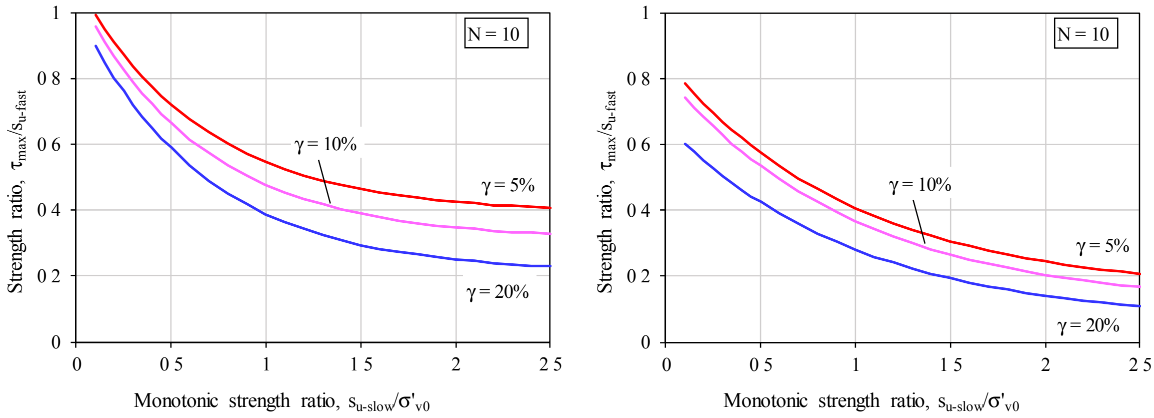


Fig. 5 Fully consolidated gain in uniaxial capacities for a 2-1 rectangular foundation



(a) 1-way cyclic loading

(b) 2-way cyclic loading

Fig. 6 Example strength reduction curves for one-way and two-way loading (10 cycles)

A simple and flexible relationship for estimating the cyclic shear stress was developed for calcareous sediments, expressed as an exponential relationship (Amodio et al. 2015):

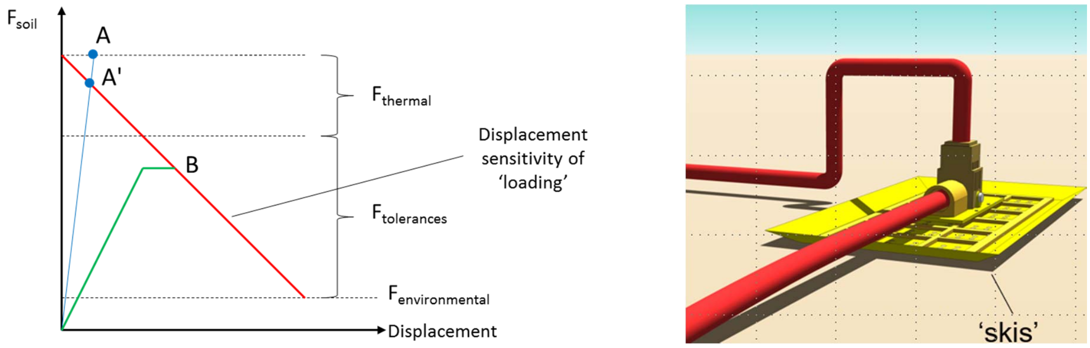
$$\frac{s_{u,cyc}}{s_{u,mono}} = a \ \exp\left(b\frac{s_{u,mono}}{\sigma'_{v0}}\right) + c \qquad [5]$$

where *a*, *b* and *c* are three fitting parameters. As few as five to ten shearing tests may be sufficient to provide an adequately conservative fit, particularly if the loading is known to be either fully one-way, or symmetric two-way. Fig. 6 shows example strength reduction curves for the two extremes of cyclic shearing. For intermediate (biased one or two-way), linear interpolation may be used. Net strength changes due to consolidation and cyclic loading will result in a fully heterogeneous pattern of shear strengths, even for sediments that are initially homogeneous with perhaps a linear strength variation with depth. Detailed assessment of stability for final design must take this into account.

Modern computing is making increasing use of the internet and cloud-based computations, facilitating access across the world and also harnessing the vast scalable power that can be brought to bear on a problem. Some of the simplified solutions discussed above have been assembled into a ‘toolbox’ of different analyses that are freely available online (Gourvenec et al. 2017). The solutions are directed more towards initial sizing of a foundation, rather than final design where greater sophistication is needed. At the opposite extreme, Doherty et al. (2018) presented a cloud-based application for assessing the combined vertical-horizontal-torsional and moment capacity of subsea foundations, under potentially hundreds of different cyclic loading cases. They described the web-based architecture required to queue jobs and enlist the necessary computing power to process the sequence of analyses required, from consolidation analyses to cyclic loading adjustments and final calculation of capacity.

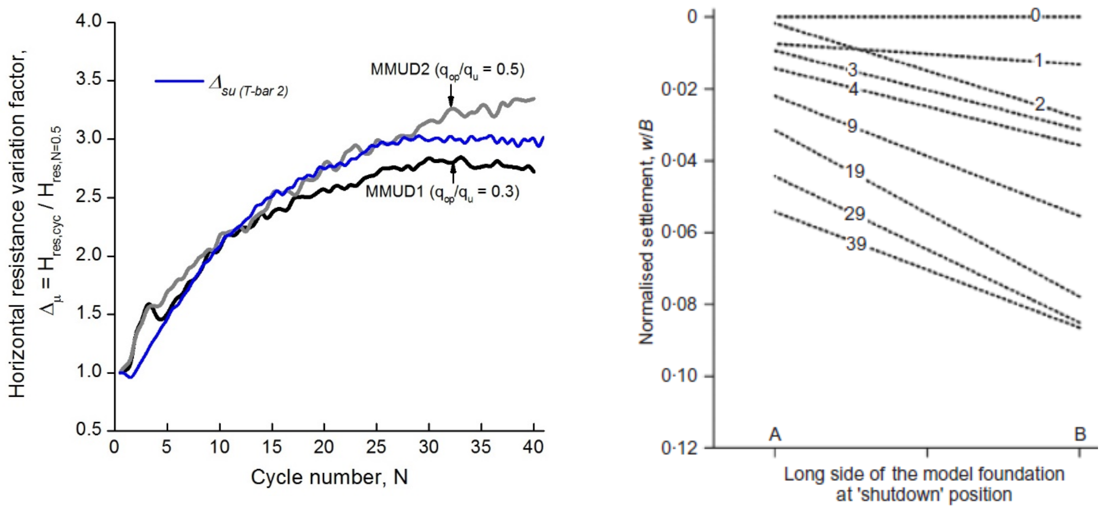
Mobility

The previous discussion was directed towards the traditional approach of ensuring stability of the foundation. However, the major part of loading that deep-water subsea foundations are subjected to arises from the pipework connected to the foundation. As such, an extreme view of the foundation would be to consider it essentially as a self-supported node within the infrastructure, allowing movement in response to the different perturbations. In reality, some constraint is required, at least in terms of bearing resistance and to avoid a dominant pipeline contraction or expansion from over stressing other connected pipelines and spools. For manifolds, with multiple connections, an iterative 'system-based' approach is logical whereby movements of the foundation under the original loads provided (generally based on a rigid foundation) allow alleviation of the loads arising from lack of fit during connection. This is indicated schematically in Fig. 7a. For simpler foundations such as PLETs, terminating a pipeline and with an additional spool connection, the mobility of the foundation can be increased to allow cyclic sliding of the foundation during each 'start-up' heating or 'shut-down' cooling of the pipeline. The design then reduces to ensuring cumulative vertical settlement and rotations do not overstress the connections, and also that the sliding resistance does not increase to the extent of causing pipeline buckling.



(a) Alleviation of loads from deformations (b) Schematic of sliding PLET

Fig. 7 Capitalising on mobility of subsea foundations



(a) Increase in horizontal resistance (b) Settlement and rotation

Fig. 8 Response of sliding foundation to periodic cycles of sliding

Sliding PLETs have started to be used in practice, with the design basis developed from physical model tests supported by analytical and numerical treatments (Deeks et al. 2014; Wallerand et al. 2015). Fig. 8 illustrates the evolution of sliding resistance, settlement and rotation from centrifuge tests where 40 full cycles of sliding and return were applied, allowing for a period of consolidation between each complete cycle to represent intervals between shut-downs (Cocjin et al. 2014). Dissipation of shear-induced excess pore pressures allows the soil beneath the foundation to strengthen as the water content is reduced, and in turn that reduces the magnitude of excess pore pressure generated during subsequent cycles of sliding. Eventually a steady state is reached with negligible pore pressure generation and the horizontal resistance reaching drained frictional sliding under the applied vertical stress, together with small amounts of ‘ploughing’ resistance, particularly at the extremes of each sliding movement. Cumulative settlements arise partly from consolidation, and partly (estimated as around 25% of the total) from physical ploughing of material leading to formation of small berms at each extreme of sliding. An analytical calculation model based on critical state concepts was shown to match the model test data well (Cocjin et al. 2017).

Formal design guidelines for subsea foundations that allow the potential for deformations that may exceed yield will need to be developed in the coming years, facilitating minimisation of foundation size without compromising the integrity of connected infrastructure. In many cases, ‘compliant’ design approaches of this type are more attractive economically than the traditional approach of ensuring adequate safety factors against the geotechnical capacity, but they will require more sophisticated understanding and modelling of the response of sediments during multiple shearing cycles (potentially to failure) in parallel with consolidation.

ANCHORING SYSTEMS

Overview

Over the last two decades there has been a proliferation of different types of anchoring systems, most of which have been inspired by the evolution from catenary mooring designs towards semi-taut and taut mooring layouts in deep water. Various of these are illustrated in Fig. 9, together with typical design load ranges. The evolution has been facilitated by mooring line technology, with the advent of polyester mooring lines (Flory et al. 2007). The various anchoring systems must therefore be capable of withstanding loads applied at angles up to 30 to 35° from the horizontal. Applications are dominated by suction caissons (Andersen et al. 2005), but rectangular plates (generally installed using a suction caisson, so called suction embedded plates – SEPLAs) and gravity-installed torpedo style anchors have also been used extensively. Also included in Fig. 9 is the dynamically embedded plate anchor (DEPLA) developed by Conleth O’Loughlin at the University of Western Australia, and now licensed commercially although yet to be used in practice. For smaller (temporary) moorings in deep water, conventional drag anchors have evolved into so-called vertically loaded anchors (VLAs) where the line of action of the mooring load relative to the anchor fluke can be increased once the anchor is embedded (Murff et al. 2005).

A number of design issues arising for different types of anchor are discussed below, not least of which is the issue of the anchor chain and its potential to create a trench in front of the anchor. Although this came to light first for suction caissons (Bhattacharjee et al. 2014), in principle the issue can arise for any type of embedded anchor where the chain angle at mudline undergoes significant variations and with a relatively high maximum angle. The consequences for design of anchoring systems are still being explored as efforts are made to develop quantitative approaches to assess potential trenching.

Plate anchors

The term ‘plate anchor’ is generic, but essentially includes any anchor where plates or flanges provide the primary resistance, for example the gravity-installed OMNI-Max anchor (Shelton 2007). The most common offshore plate anchor is the SEPLA, which was developed some 20 years ago (Dove et al. 1998, Wilde et al. 2001). Interestingly, the Omni-Max and SEPLA show different responses during loading, with the former tending to dive deeper into the seabed, while the latter loses embedment monotonically and eventually pulls out. So, while plate anchors need to be installed in a vertical plane, differences in behaviour emerge during ‘keying’ and subsequent loading to failure, a key factor being the angle subtended by the mooring chain to the normal to the plate at the various stages of keying and loading to failure.

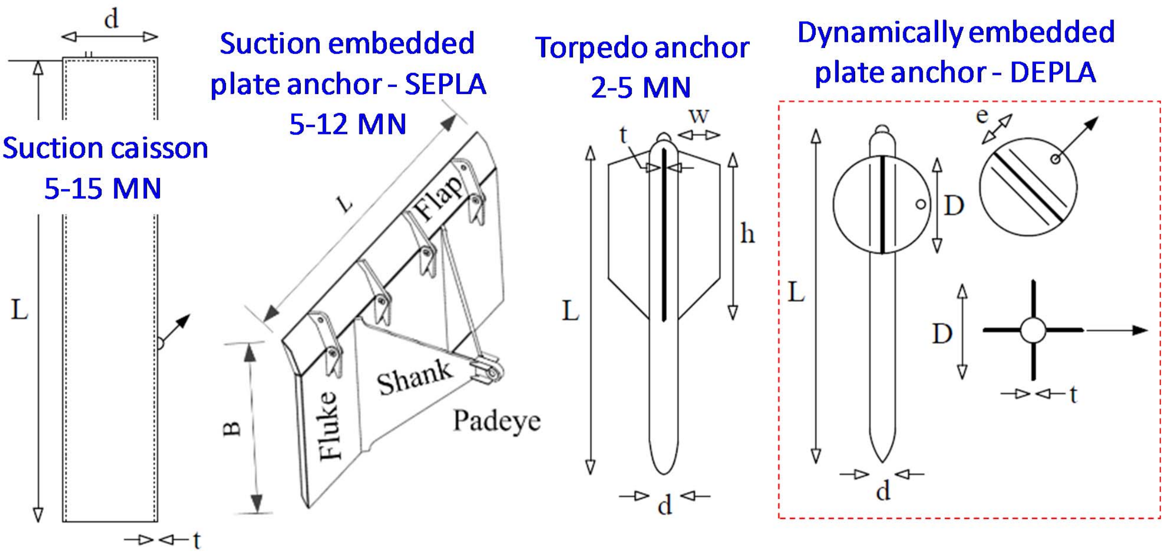


Fig. 9 Illustration of various anchor types for deep water

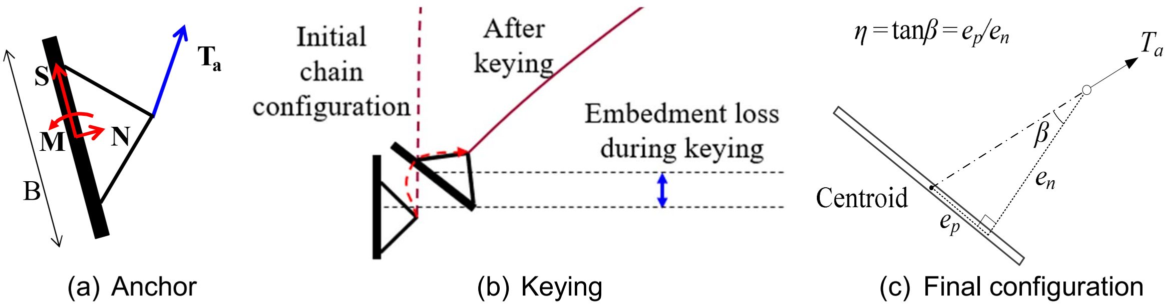


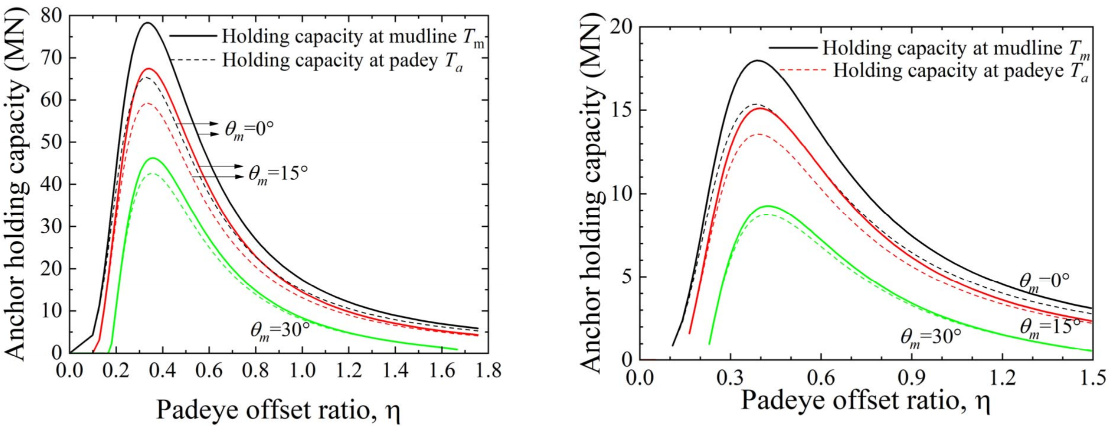
Fig. 10 Schematics of plate anchor response

A design approach was developed for the standard SEPLA design, allowing for (Wong et al. 2012):

1. loss of embedment during keying (Fig. 10b);
2. strain-softening of the soil;
3. reduction factor on theoretical bearing capacity due to plate angle;
4. effects of cyclic and sustained loading.

The starting point for design is the soil shear strength at the original (known) embedment depth of the anchor (i.e. combined fluke plus keying flap) centroid, together with the relevant bearing capacity factor for a rectangular plate of N_c = 14. Each of the factors above reduce the design anchor capacity (even without a material factor) from 14 by approximately half, to $N_{c,design}$ ~ 7-7.5.

Physical and numerical modelling has been used to explore how the current SEPLA design (and that of other plate anchors) can be improved. The key lies in the offset geometry of the padeye (chain attachment point), which is offset by e_p parallel to the fluke and e_n normal to the fluke (Fig. 10c). Then, once all rotation has ceased and so no moment is applied to the anchor, the chain load subtends an angle β with the normal to the fluke where tanβ = e_p/e_n. As summarised by Tian et al. (2020a), for a given anchor type there are optimal ranges for the padeye offset ratio η = tanβ that will cause the anchor to dive, rather than pull out towards the surface. For a given mudline chain angle θ_m and chain properties, a theoretical ultimate dive depth, and hence ultimate capacity, can be calculated by combining the analytical solution for the curved geometry of the chain (Neubecker and Randolph 1995) with the yield envelope in normal (*N*), shear (*S*) and moment (*M*) load space for the given anchor (Tian et al. 2015).



(a) SEPLA (b) OMNI-Max

Fig. 11 Theoretical ultimate holding capacities for SEPLA and OMNI-Max

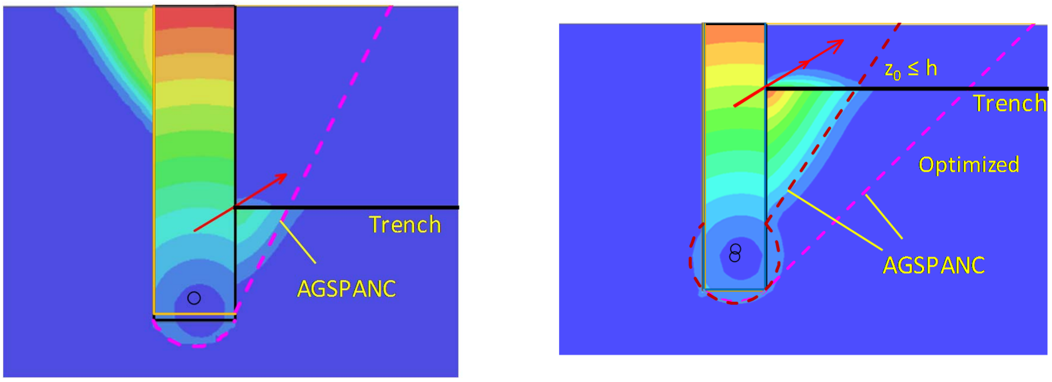
Example plots of the ultimate anchor holding capacity are shown in Fig. 11 for the SEPLA and OMNI-Max geometries, assuming a soil shear strength profile of s_u = 1.25z kPa and a chain bar diameter of 0.1 m (Tian et al. 2020a). The maximum capacities shown, which vary according to the projected areas of the anchors, are somewhat academic (in the sense of impractical – aren't we all!) in that a chain of 0.1 m diameter would not be able to withstand those holding capacities, while thicker chain would increase the curvature within the soil, so limiting embedment to a shallower depth. For example, doubling the chain bar diameter would halve the maximum holding capacity for θ_m of zero. However, the plots illustrate how the anchor design may be optimised, e.g. with padeye offset ratios in the range 0.3 to 0.4. The current SEPLA geometry has a lower offset ratio (~ 0.2) while that for the OMNI-Max, as deduced from 3-D finite element analyses (Wei et al. 2015), is on target at ~ 0.35. Indeed, the diving performance of the OMNI-Max anchor has been well demonstrated, as a result of Hurricane Gustav in the Gulf of Mexico, where line-breakage led to overloading of several anchors, causing them to dive (Zimmerman et al. 2009).

An obvious advantage of anchors that are designed to dive is that their holding capacity becomes independent of the initial embedment depth, provided that is sufficient to initiate the diving process without the anchor pulling out during keying. The relatively simple torpedo anchors that were developed and used extensively in Brazilian waters (Medeiros 2001; Araujo et al. 2004), do not have that capability and so are more vulnerable to the quality of the free-fall installation. The dynamically embedded plate anchor (DEPLA), which combines a free-falling (retrievable) torpedo mandrel with a cruciform plate anchor has high potential. In its original form the chain attachment was envisaged at the mid-point of one of the plates, so zero offset ratio (see Fig. 9), but the design can be improved significantly by lowering the attachment point to an appropriate offset ratio to enable diving as the load is increased (Tian et al. 2020b).

Trenches

Design approaches for suction caissons as mooring line anchors are now well established, in terms of both installation and operational capacity. Generally, the padeye is placed at a depth where, under the maximum design load (which will also coincide with the steepest chain angle), the centre-line intersection of the anchor load is close to that causing minimal rotation of the caisson (Andersen et al. 2005). However, the discovery of deep trenches created by anchor chain motions in front of suction caissons has complicated the picture. As quantitative approaches are developed to estimate the extent and time scale of trench development for different mooring configurations and soil types, a necessarily conservative design basis needs to be adopted. These include assumption of full (caisson) width trenches that may extend down to the padeye, and potential for forward tilt with loss of suction behind the caisson. The choice, discussed further in Randolph et al. (2020), is then between a deep padeye, possibly slightly deeper than for the untrenched optimal depth, or a much shallower padeye, balancing the reduction in caisson capacity arising from greater rotation against the reduced loss of soil support from a shallower trench. Fig. 12 compares these two situations, and also the failure mechanisms from ABAQUS (Dassault Systèmes 2014) and the design tool

AGSPANC - the latter based on the excellent upper bound solution for laterally loaded piles of Murff and Hamilton (1993).



(a) Deep padeye (b) Shallow padeye

Fig. 12 Comparison between ABAQUS and AGSPANC of failure mechanisms including trenches

While the potential for trench formation has, at this stage, been focused on suction caissons, other embedded anchors such as SEPLAs and the OMNI-Max, if used for permanent semi-taut moorings, may also be vulnerable to reduction in capacity from trenches. It will no doubt take a few years more until robust design methods, or mitigation methods to avoid trench formation, are developed for these various anchor types.

AUSTRALIAN OFFSHORE OIL AND GAS DEVELOPMENTS

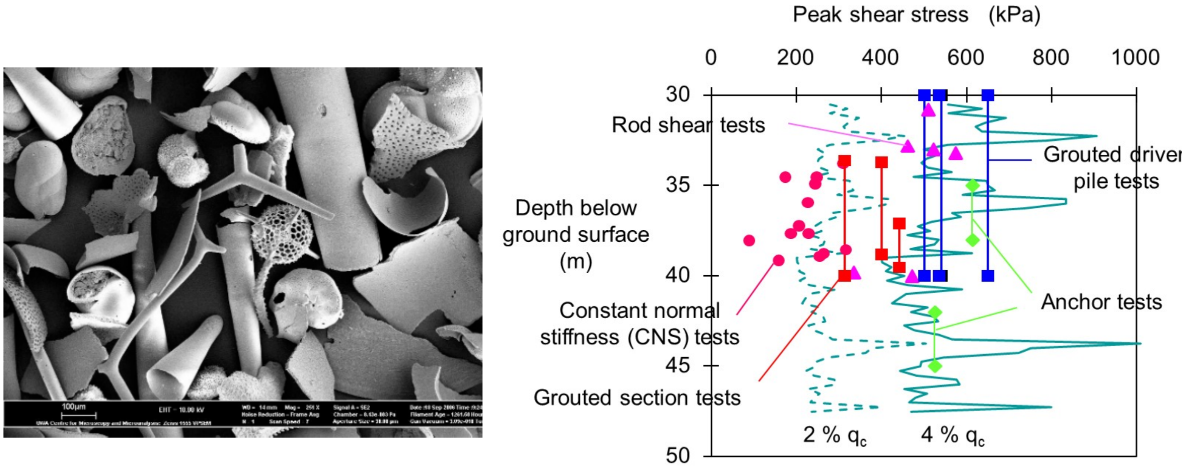
Overview

In the last part of this paper, I shall return to developments in Australia, both technical aspects and in the growth in offshore geotechnics expertise over the last three decades. On the technical side, in broadly chronological order, I will touch on the carbonate sediments off the north west of Australia and how they have affected foundation design, the introduction of full-flow penetrometers (for which I tend to get blamed) and then our transition to deep water beyond the continental shelf break.

Carbonate sediments

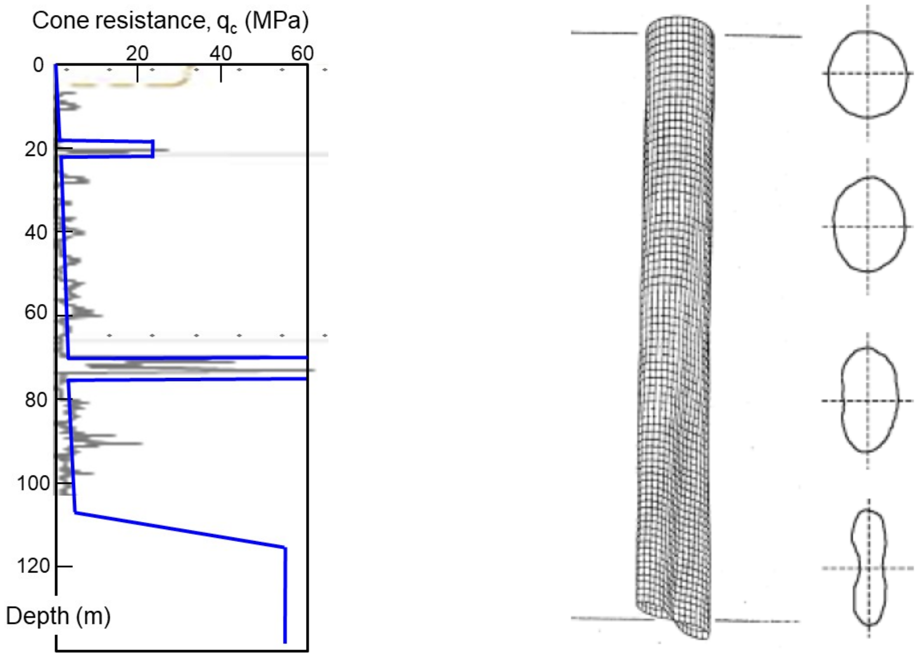
One of the most challenging aspects of carbonate sediments is their stratification and spatial variability, typically with relatively strong cemented material, calcarenite, interbedded within weak carbonate silts. The consequences of the latter became evident in the extremely low shaft friction for driven piles, which results from the crushable nature of the material (see Fig. 13a) and also the high friction angles and light in situ cementation that facilitate arching, leading to low normal effective stresses acting on the pile. Generally, more consistently cemented material is encountered at depth, although in the vicinity of the early gas platforms, North Rankin A (NRA) and Goodwyn, not till around 110 m below mudline. Since NRA, the majority of the larger piled jacket structures have adopted a primary pile driven through the uncemented material, below which a secondary insert pile is grouted into cemented material. In developing design parameters for the Goodwyn drilled and grouted piles, Woodside undertook field tests in a weak limestone at Overland Corner, South Australia. Typical strength data for this material, which has an average cone resistance of around 13 MPa, are shown in Fig. 13b (Randolph et al. 1996).

Ironically, the Goodwyn primary piles, which were installed towards the end of 1992, suffered a rather different form of problem than those at NRA. The 2.65 m diameter primary piles were designed with a wall thickness of 45 mm, so diameter to wall thickness ratio of 59. Although this is relatively high, easy driving was expected. In practice, however, many of the piles deformed severely over the bottom 20 to 40 m, preventing drilling out to install the grouted inserts (see Fig. 14b). The main trigger for the distortion was the rather strong cemented layer at 75 m depth (Fig. 14a), possibly exacerbated by minor damage to the pile tip occurring during handling and stabbing the piles through a seabed template (Senders et al. 2013). The piles were eventually remediated sufficiently, using a combined process of crocodile jacks and internal pressurisation (Barbour and Erbrich 1994), to allow construction of the grouted insert piles as originally planned.



(a) Uncemented carbonate sediment (b) Strengths in cemented calcarenite

Fig. 13 Soft and strong – contrasting material properties



(a) Cone resistance profile (b) Consequences of pile driving

Fig. 14 Striking the balance for pile driving

Pile tip damage, either in the form of local crumpling or the more gradual deformation referred to as extrusion buckling is more common than is generally realised, and has increased in frequency in the offshore wind industry, where piles with diameters up to 7.5 m have been used for driving into different sediments such as partially weathered mudstone, dense sands or weak limestone. Centrifuge model tests to explore this are reported by Nietiedt et al. (2020). In Australia, although we have yet to develop offshore wind farms, relatively large (5.5 m diameter) driven piles have been used to anchor floating offshore facilities, including the world-first FLNG tanker at Shell's Prelude field. The anchor piles incorporated devices to limit free-fall speed through uncemented carbonate silts, but also thickened driving shoes and cruciform internal stiffeners to avoid pile tip damage during driving through cemented layers (Frankenmolen et al. 2017; Erbrich et al. 2017). Design of the piles relied on the state-of-art numerical tool, BASIL, developed originally for suction buckets in the North Sea (Barbour and Erbrich 1995; Erbrich et al. 2010a).

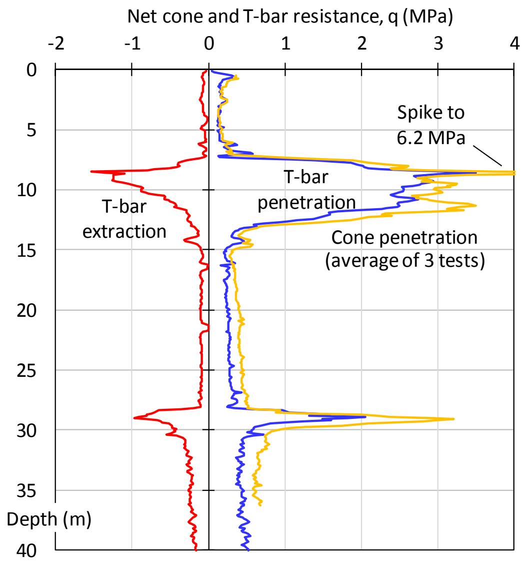
The brittle pile-soil shear response for drilled and grouted piles necessitated more sophisticated treatment of the effects of cyclic loading. For Goodwyn, axial load transfer software RATZ (Randolph 1994) was developed to allow cycle-by-cycle analysis of tens of thousands of load cycles representing design storm and life-time loading. The original load transfer algorithm was later enhanced in proprietary software CYCLOPS, with particular attention to the evolution of the shear stress variation during post-peak cyclic shearing in order to match field and laboratory test data. Details of this, and the form of laboratory tests required for calibration of the load transfer algorithms were provided in Erbrich et al. (2010b).

Full-flow penetrometers

Evolution of the Australian oil and gas industry to floating facilities in deeper water, where the sediments tended to be more fine-grained and softer, provided the impetus to trial a new type of penetrometer. The T-bar penetrometer had been developed at the University of Western Australia in the early 1990s, primarily to improve characterisation of soil samples in centrifuge tests (Stewart and Randolph 1991). In 1997, Fugro were asked by Woodside to develop a field version, which was used for the Laminaria site investigation in the Timor Sea (Randolph et al. 1998). Subsequently, in 1998, its use was extended for the early SI stages of Chevron's Gorgon project (Hefer and Neubecker 1999), and also for Shell's Bonga field off the coast of West Africa.

Full-flow penetrometers, originally the T-bar, but now increasingly the ball penetrometer – equipped with pore pressure sensors as a piezoball to allow deduction of consolidation properties – have since become relatively routine for near-surface soft sediments, with particular application for pipeline and shallow foundation or anchor design, joining conventional cone penetrometers (Fig. 15a). Although targeted at soft sediments, where the ability to cycle the penetrometer to obtain remoulded resistances is an added attraction, it is commonly pushed through cemented carbonate layers, where resistances of several MPa may be encountered (Fig. 15b). A joint industry project, led by the Norwegian Geotechnical Institute, reviewed a worldwide database of penetrometer data, which led to recommendations for suitable penetrometer factors and guidelines for conducting such tests (Low et al. 2010; Lunne et al. 2011).

(a) T-bar, ball and cone penetrometers

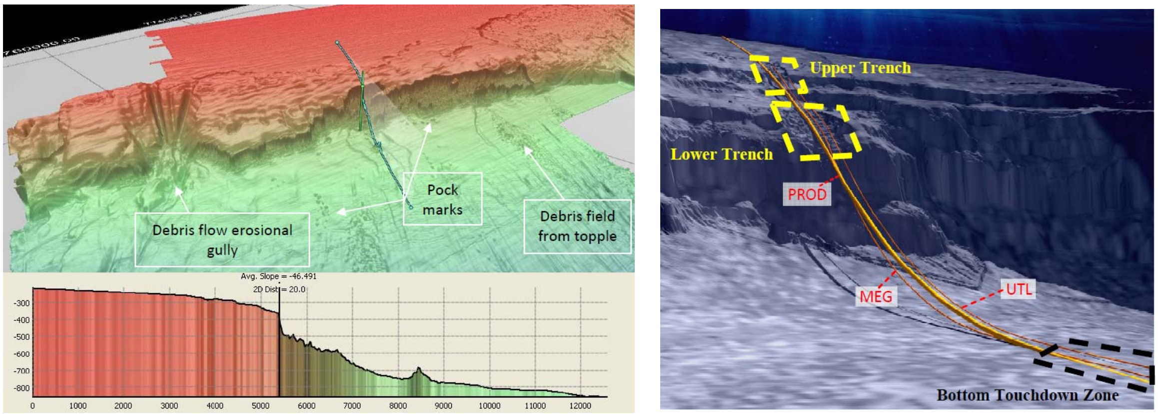


(b) Resistance profiles at Gorgon

Fig. 15 Varieties of penetrometer and resistance profiles in carbonate sediments

Off the shelf – Jansz super-span

The development of the Greater Gorgon field in the period 2010-2015 introduced a significant change in focus of offshore activities in respect of the Jansz and Io reservoirs, which were in water depths of around 1200 m. The development adopted a subsea approach (Fig. 2), but perhaps the most significant challenge of the development lay in routing the export pipeline up the steep scarp separating the Gorgon field (200 m water depth) and the deep water Jansz and Io fields. The nature of the scarp is illustrated graphically in Fig. 16 (Hengesh et al. 2012). In addition to finding a suitable route up the scarp itself, the geohazard risks to the pipeline from submarine landslides and consequential debris flows and gas expulsion features needed to be assessed.



(a) Gorgon landslide scarp (b) Scarp crossing with super-span

Fig. 16 Challenges of deep water developments for Greater Gorgon project

The scarp contains localised zones where the gradient is close to vertical with significant drops of ~10 m. Sediments above and below the scarp are essentially normally consolidated, and there is no evidence of cementation per se in the sediments on the scarp itself, other than due to interlocking. Near surface strengths reach 20 kPa, with peak friction angles close to 50° (Zhang et al. 2015). Geochronology played a major role in assessing the natural slope stability, given this combination of steep gradients and relatively low shear strengths. An innovative solution for the scarp crossing was arrived at, as indicated in Fig. 16b, which shows the main 30" production pipeline and smaller 8" and 6" lines for monoethylene glycol (MEG) and utilities (UTL), respectively, descending the scarp between water depths of about 500 m and 800 m (Zhang et al. 2015). The pipeline curvature over the upper part of the scarp was alleviated by trenching using mechanical grabs, which were found to be more robust than water jetting tools. The lower part of the scarp was bridged by a suspended section of pipeline, aptly referred to as the 'super-span', some 270 m long. Sophisticated engineering studies, including centrifuge model testing at UWA, were undertaken to address design issues associated with the super-span, including fatigue due to VIV induced by transverse currents, and embedment at the lower end of the span due to pipe weight and cyclic loading from 'slugging' of mixed phase pipe contents (Zhang et al. 2015).

Symbiotic relationship between university and industry

It is fitting to end this paper with some comments on the broader picture of offshore geotechnical engineering in Perth, and indeed internationally. One of the great strengths in developing scientific approaches to the treatment of Australia's offshore carbonate sediments has been the close symbiotic relationship between industry and academia, principally the Centre for Offshore Foundation Systems (COFS) at UWA. The latter was funded as an Australian Research Council Special Research Centre over the period 1997-2005, by the WA State Government as a Centre of Excellence 2007-2012 and as a node of the Australian Research Council Centre of Excellence in Geotechnical Science and Engineering (CGSE) 2011-2017.

The main industry partner during the rapid expansion of the North West Shelf was the specialist offshore geotechnical consultancy, Advanced Geomechanics (AG), over the period 1994, when it was founded - the inspiration of Dr Mohamed Khorshid on leaving Woodside, to the end of 2013 when it was acquired by Fugro. AG provided the link to ultimate clients such as Woodside, Chevron and the Gorgon Joint Venture, Inpex, Shell and many others, and for many years all advanced laboratory and centrifuge model testing was conducted in the facilities developed by COFS. This collaboration is described further in an invited paper to mark the Australian Geomechanics Society's 50th year (Randolph 2020).

The final word must, of course, go to ISFOG itself. When we proposed the first International Symposium on Frontiers in Offshore Geomechanics, held in Perth in 2005, we little knew that it would acquire a life of its own. Much of the credit for this goes to Susan Gourvenec, Chair of the first two conferences and still much involved in helping to maintain the high standards the series has achieved. With some reservations it was allowed to escape cavity to Oslo in 2015 and then to Austin in 2020 (at least nominally, given that as I write this the whole world is in lock down, courtesy of the COVID-19 virus). I think it has also been bequeathed for 2025, but rest assured we would like our ball back at some stage, perhaps 2030 though I no longer plan that far ahead!

ACKNOWLEDGEMENTS

This paper has drawn, at least in part, on activities of the Centre for Offshore Foundation Systems (COFS), supported variously by the Australian Research Council, the WA State Government and through the Fugro Chair in Geotechnics, the Lloyd's Register Foundation Chair and Centre of Excellence in Offshore Foundations and the Shell Chair in Offshore Engineering. Grateful thanks are also due to the many colleagues who have contributed so much to a really fun 'lifetime' in offshore geotechnics - colleagues who are spread among UWA, the former Advanced Geomechanics and now Fugro, NGI and other companies and universities in Perth and overseas. Although somewhat invidious (and I apologise in advance for forgetting someone vital!), I would like to single out a number of individuals who have influenced, assisted or sustained me significantly through my career, either as mentors or colleagues. These include Mark Cassidy and Christophe Gaudin, Directors of COFS since 2006; Managing Directors of AG, Mohamed Khorshid and Phil Watson; Technical Director of AG, Carl Erbrich; industry personnel Don Murff, Ed Clukey, Philippe Jeanjean, Knut Andersen and Tom Lunne; and UWA colleagues Richard Jewell, Martin Fahey, Fraser Bransby, Susan Gourvenec, Dave White, Yuxia Hu and Barry Lehane. And that's not counting my current young collaborators - the list could be, and in reality is, a lot longer…

REFERENCES

AGSPANC 2001. AGSPANC: Suction pile analysis code: Users' Manual, Version 3.0. Advanced Geomechanics (now Fugro).

Alm, T. and Hamre, L. 2001. Soil model for pile driveability based on CPT interpretations. Proc. 15th Int. Conf. on Soil Mechanics and Geotech. Eng., Istanbul, Taylor and Francis, London, 2, 1297-1302.

Amodio, A., Chang, T.M., Kong, V. and Erbrich C.T. 2015. The effects of jack-up installation procedures on spudcan capacity in offshore carbonate sediments. Proc. 3rd Int. Symp. on Frontiers in Offshore Geotech., ISFOG 2015, Taylor and Francis, London, 1253-1260.

Andersen, K.H. 2015. Cyclic soil parameters for offshore foundation design. 3rd McClelland Lecture, Proc. 3rd Int. Symp. on Frontiers in Offshore Geotech., ISFOG 2015, Taylor and Francis, London, 5-82.

Andersen, K.H., Lunne, T., Kvalstad, T., Forsberg, C.F. 2008. Deep water geotechnical engineering. Proc. XXIV Nat. Conf. Mexican Soc. of Soil Mechanics, Aguascalientes, 1-57.

Andersen, K.H., Murff, J.D., Randolph, M.F., Clukey, E., Erbrich, C.T., Jostad H.P., Hansen, B., Aubeny, C.P., Sharma, P. and Supachawarote, C. 2005. Suction anchors for deepwater applications. Proc. Int. Symp. on Frontiers in Offshore Geotechnics, ISFOG, Perth, Taylor and Francis, London, 3-30.

API 2011. Recommended Practice 2GEO Geotechnical and Foundation Design Considerations – 1st Edition. American Petroleum Institute, Washington.

Araujo, J.B., Machado, R.D. and Medeiros, C.J. 2004. High holding power torpedo pile – results for the first long term application. Proc. 23rd Int. Conf. Offshore Mech. and Arctic Eng., ASME, Vancouver, OMAE2004-51201.

Barbour, R.J. and Erbrich, C.T. 1994. Analysis of in-situ reformation of flattened large diameter foundation piles, using ABAQUS. Proc. UKABAQUS Users Conf., Oxford.

Barbour, R.J. and Erbrich, C.T. 1995. Analysis of soil-skirt interaction during installation of bucket foundations, using ABAQUS. Proc. ABAQUS Users Conf., Paris.

Bhattacharjee, S., Majhi, S.M., Smith, D. and Garrity, R. 2014. Serpentina FPSO mooring integrity issues and system replacement: unique fast track approach. Proc. Offshore Technology Conf., Houston, OTC 25449.

Broadway, T. and Tachoires, V. 2016. Structures deepwater installation challenges – North West Shelf, Australia. Proc. Offshore Technology Conf., Kuala Lumpur, OTC 26720.

Burd, H.J., Taborda, D.M.G., Zdravkovic, L., Abadie, C.N., Byrne, B.W. Houlsby, G.T., Gavin, K., Igoe, D., Jardine, R.J., Martin, C.M., McAdam, R.A., Pedro, A.M.G. and Potts, D.M. 2020. PISA design model for monopiles for offshore wind turbines: Application to a marine sand. Géotechnique, 70 (in press).

Byrne, B.W. Houlsby, G.T., Burd, H.J., Gavin, K., Igoe, D., Jardine, R.J., Martin, C.M., McAdam, R.A., Potts, D.M., Taborda, D.M.G. and Zdravkovic, L. 2020. PISA design model for monopiles for offshore wind turbines: Application to a stiff glacial clay till. Géotechnique, 70 (in press).

Clausen, C.J. F., Aas, P.M. and Karlsrud, K. 2005. Bearing Capacity of Driven Piles in Sand, the NG/ Approach, ISFOG 2005, Proc. 1st Int. Symp. on Frontiers in Offshore Geotechnics, Perth, Taylor and Francis, London, 677-682.

Cocjin, M.L., Gourvenec, S.M., White, D.J. and Randolph, M.F. 2014. Tolerably mobile subsea foundations – Observations of performance. Géotechnique, 64(11) 895-909.

Cocjin, M.L., Gourvenec, S.M., White, D.J. and Randolph, M.F. 2017. Theoretical framework for predicting the response of tolerably mobile subsea installations. Géotechnique, 67(7) 608–620.

Dassault Systèmes 2014. *ABAQUS 6.14 Analysis User's Manual*, Simulia Corp, Providence, RI.

Deeks, A., Zhou, H., Krisdani, H., Bransby, M.F. and Watson, P.G. 2014. Design of direct on-seabed sliding foundation. Proc. 33rd Int. Conf. Ocean, Offsh. and Arctic Eng., San Fran., OMAE2014-24393.

Demel, J., Wallerand, R., Rebours, N., Cafi, M., Grelon, F., Mencarelli, G., Gioielli, P. and Olayera, O. 2016. Pipeline walking mitigation by anchor in-line structures with the use of a hybrid subsea foundation. Proc. Offshore Technology Conf., Houston, OTC-27295.

Dimmock, P., Clukey, E.C., Randolph, M.F., Gaudin, C. and Murff, J.D. 2013. Hybrid subsea foundations for subsea equipment. J. of Geot. and Geoenv. Eng., ASCE, 139(12) 2182-2192.

Doherty, J.P., Krisdani, H., O'Neill, M.P., Erbrich, C.T., Bransby, M.F., White, D.J. and Randolph, M.F. 2018. The design of subsea foundations subject to general cyclic loading using a massively scalable web based application. Proc. Offshore Technology Conf., Houston, OTC 28991.

Dove, P., Treu, H. and Wilde, B. 1998. Suction embedded plate anchor (SEPLA): a new anchoring solution for ultra-deepwater mooring. Proc. Deep Offshore Tech. Conf, New Orleans.

Dyson, G.J. and Randolph, M.F. 2001. Monotonic lateral loading of piles in calcareous sediments. J. Geotech Eng. Div, ASCE, 127(4) 346-352.

Erbrich, C.T., Barbosa-Cruz, E. and Barbour, R.J. 2010a. Soil-pile interaction during extrusion of an initially deformed pile. Proc. 2nd Int. Symp. on Offshore Geotechnics, Perth, Taylor and Fracis, London, 489-494.

Erbrich, C.T., Lam, S.Y., Zhu, H., Derache, A., Sato, A. and Al-Showaiter, A. 2017. Geotechnical design of anchor piles for Ichthys CPF and FPSO. Proc. 8th Int. Conf. Offshore Site Investigation and Geotechnics, Society for Underwater Technology, London, 2, 1186-1197.

Erbrich, C.T., O'Neill, M.P., Clancy, P. and Randolph, M.F. 2010b. Axial and lateral pile design in carbonate soils, Keynote Lecture. Proc. 2nd Int. Symp. on Frontiers in Offshore Geotechnics, ISFOG 2010, Perth, Taylor and Francis, London, 125-154.

Feng, X. and Gourvenec, S. 2015. Consolidated undrained load-carrying capacity of mudmats under combined loading in six degrees-of-freedom. Géotechnique, 65(7) 563-575.

Feng, X., Randolph, M.F., Gourvenec, S. and Wallerand, R. 2014. Design approach for rectangular mudmats under fully three-dimensional loading. Géotechnique, 64(1) 51-63.

Feng, X., Randolph, M., Gourvenec, S., Wallerand, R. and Dimmock, P. 2015. Effect of a surficial crust on mudmat capacity under fully three-dimensional loading. Géotechnique, 65(7) 590-603.

Flory, J.F., Banfield, S.J. and Berryman, C. 2007. Polyester mooring lines on platforms and MODUs in deep water. Proc. Offshore Technology Conf., Houston, OTC 18768.

Frankenmolen, S., Erbrich, C.T. and Fearon, R. 2017. Successful installation of large suction caissons and driven piles in carbonate soils. Proc. 8th Int. Conf. Offshore Site Investigation and Geotechnics, Society for Underwater Technology, London, 1, 539-548.

Gaudin, C., Randolph, M.F., Feng, X., Clukey, E.C. and Dimmock, P. 2012. Centrifuge modelling of a hybrid foundation for subsea equipment. Proc. 7th Int. Conf. Offshore Site Investigation and Geotechnics, Society for Underwater Technology, London, 411-420.

Gourvenec, S., Feng, X., Randolph, M.F. and White, D.J. 2017. A toolbox for optimizing geotechnical design of subsea foundations. Proc. Offshore Technology Conf., Houston, OTC 27703.

Gourvenec, S., Vulpe, C. and Murthy, T. 2014. A method for predicting the consolidated undrained capacity of shallow foundations on clay. Géotechnique, 64(3) 215-225.

Hefer, P.A and Neubecker, S.R. 1999. A recent development in offshore site investigation tools: the T-bar. Proc. Australasian Oil and Gas Conf., Perth.

Hengesh, J.V., Dirstein, J.K. and Stanley, A.J. 2012. Seafloor geomorphology and submarine landslide hazards along the continental slope in the Carnarvon Basin, Exmouth Plateau, North West Shelf, Australia. APPEA Journal 2012, 493-511.

ISO 2016. ISO19901-4: Petroleum and natural gas industries specific requirements for Offshore Structures - Part 4: Geotechnical and foundation design considerations - 2nd Edition. International Standards Organisation, Geneva.

Jardine, R., Chow, F., Overy, R. and Standing, J. 2005. ICP Design Methods for Driven Piles in Sands and Clays, Imperial College, Thomas Telford Publishing, London.

Jeanjean, P. 2009. Re-assessment of p-y curves for soft clays from centrifuge testing and finite element modelling. Proc. Offshore Technology Conf., Houston, OTC 20158.

Kallehave, D., Byrne, B.W., LeBlanc Thilsted, C., Mikkelsen, K.K. 2015. Optimization of monopiles for offshore wind turbines. Phil. Trans. Royal Society A: Mathematical, Physical and Engineering Sciences. 373. https://doi.org/10.1098/rsta.2014.0100.

Kolk, H.J., Baaijens, A.E. and Senders, M. 2005. Design criteria for pipe piles in silica sands. Proc. 1st Int. Symp. on Frontiers in Offshore Geotechnics, Taylor and Francis, London, 711-716.

Kraft L.M. 1982. Effective stress capacity model for piles in clay. J. Geot. Eng. Div., ASCE, 108 (GT11) 1387-1404.

Lehane, B.M., Bittar, E.., Nadim, F., Lacasse, S., Jardine, R.J., Carotenuto, P., Rattley, M., Jeanjean, P., Gavin, K., Gilbert, R., Haavik, J.B. and Morgan, N. 2020. A new 'unified' CPT-based axial pile capacity design method for driven piles in sand. Proc. 4th Int. Symp. On Frontiers in Offshore Geotechnics, ISFOG 2020, Austin, Texas, August 2020 (in press).

Lehane, B.M., Jardine, R.J., Bond, A.J. and Frank, R. 1993. Mechanisms of shaft friction in sand from instrumented pile tests, J. Geot. Eng. Div., ASCE, 119(1) 19-35.

Lehane, B.M., Schneider, J.A. and Xu, X. 2005. A Review of Design Methods for Offshore Driven Piles in Siliceous Sand. Research Report Geo:05358, Geomechanics Group, The University of Western Australia.

Low, H.E., Lunne, T., Andersen, K.H., Sjursen, M.A., Li, X. and Randolph, M.F. 2010. Estimation of intact and remoulded undrained shear strength from penetration tests in soft clays. Géotechnique, 60(11) 843-859.

Lunne, T., Andersen, K.H., Low, H.E., Sjursen, M., Li, X. and Randolph, M.F. 2011. Guidelines for offshore in situ testing and interpretation in deep water soft soils. Canadian Geotechnical J., 48(6) 543-556.

Medeiros, C.J. 2001. Torpedo anchor for deep water. Proc. Deep Offshore Technology Conf., Rio de Janeiro.

Murff, J.D. and Hamilton, J.M. 1993. P-Ultimate for undrained analysis of laterally loaded piles, Journal of Geotech. Engng, ASCE, 119 (1) 91-107.

Murff, J.D., Randolph, M.F., Elkhatib, S., Kolk, H.J., Ruinen, R., Strom, P.J. and Thorne, C. 2005. Vertically loaded plate anchors for deepwater applications. Proc. Int. Symp. on Frontiers in Offshore Geotechnics, ISFOG, Perth, Taylor and Francis, London, 31-48.

Nadim, F., Lacasse, S., Liu, Z. and Lehane, B.M. 2020. Improving the reliability of the calculated axial capacity of piles in sand. Proc. 4th Int. Symp. On Frontiers in Offshore Geotechnics, ISFOG 2020, Austin, Texas, August 2020 (in press).

Neubecker, S.R. and Randolph, M.F. 1995. Profile and frictional capacity of embedded anchor chains. J. Geotech. Engng, ASCE, 121(11) 797–803.

Nietiedt, J., Randolph, M.F., Gaudin, C., Doherty, J.P., Kallehave, D., Gengenbach, J. and Shonberg, A. 2020. Physical modelling of pile tip damage arising from impact driving. Proc. 4th Int. Symp. on Frontiers in Offshore Geotechnics, ISFOG 2020, Austin (in press).

Novello, E.A. 1999. From static to cyclic p–y data in calcareous sediments. In Engineering for Calcareous Sediments (ed. K. Al-Shafei), Balkema, Rotterdam, 1, 17–24.

Randolph, M.F. 1994. RATZ – Load Transfer Analysis of Axially Loaded Piles, User Manual. [current version RATZ 4.2 (2003)].

Randolph, M.F. 2013. 2nd McClelland Lecture: Analytical contributions to offshore geotechnical engineering. Proc. 18th Int. Conf. on Soil Mechanics and Geotech. Engng, Paris, 85-105.

Randolph, M.F. (2020). Offshore oil and gas facilities in the north-west. In Commemorating 50 Years of the Australian Geomechanics Society (in press).

Randolph, M.F., Doherty, J.P., O'Neill, M.P., Feng, X., Ballard, J.-C. and Melo, C. 2020. Analysis and design of suction anchors allowing for trench. Proc. 4th Int. Symp. on Frontiers in Offshore Geotechnics, ISFOG 2020, Austin (in press).

Randolph, M.F., Hefer, P.A., Geise, J.M. and Watson, P.G. 1998. Improved seabed strength profiling using T-bar penetrometer. Proc Int. Conf. Offshore Site Investigation and Foundation Behaviour - New Frontiers, Society for Underwater Technology, London, 221-235.

Randolph M.F., Joer H.A., Khorshid M.S. and Hyden A.M. 1996. Field and laboratory data from pile load tests in calcareous soil. Proc. Offshore Technology Conf., Houston, OTC 7992.

Randolph, M.F. and Houlsby, G.T. 1984. The limiting pressure on a circular pile loaded laterally in cohesive soil. Géotechnique, 34(4) 613-623.

Randolph, M.F. and Murphy, B.S. 1985. Shaft capacity of driven piles in clay. Proc. Offshore Technology Conf., Houston, OTC 4883.

Senders, M., Banimahd, M., Zhang, T. and Lane, A. 2013. Piled foundations on the North West Shelf. Australian Geomechanics, 48(4) 149-160.

Shelton, J.T. 2007. OMNI-Max anchor development and technology. Proc. 2007 Oceans Conf., Vancouver, Canada.

Stewart, D.P. and Randolph, M.F. 1991. A new site investigation tool for the centrifuge. Proc. Int. Conf. on Centrifuge Modelling - Centrifuge 91, Boulder, Colorado, 531-538.

Suryasentana, S.K. and Lehane, B.M. 2014. Numerical derivation of CPT-based p-y curves for piles in sand. Géotechnique, 64(3) 186-194.

Tian, Y., Cassidy, M.J. and Randolph, M.F. 2020a. Optimising anchor design to achieve greater embedment depth and holding capacity. Proc. 4th Int. Symp. on Frontiers in Offshore Geotechnics, ISFOG 2020, Austin (in press).

Tian, Y., O'Loughlin, C. and Cassidy, M.J. 2020b. Optimisation of the padeye position of dynamically embedded plate anchors. Under review.

Tian, Y., Randolph, M.F. and Cassidy, M.J. 2015. Analytical solution for ultimate embedment depth and potential holding capacity of plate anchors. Géotechnique, 65(6) 517-530.

Vesic, A.S. 1977. Design of Pile Foundations, National Co-operative Highway Research Program, Synthesis of Highway Practice No 42, Trans. Res. Board, National Res. Council, Washington DC.

Vulpe, C., Gourvenec, S. Leman, B. and Fung, K.N. 2016. Failure envelopes for consolidated undrained capacity of strip and circular surface foundations. J. of Geot. and Geoenv. Eng., ASCE,, 142(8), http://dx.d0i.org/10.1061/(ASCE)GT.1943-5606.0001498).

Wallerand, R., Stuyts, B., Blanc, M., Thorel, L. and Brown, N. 2015. A design framework for sliding foundations: centrifuge testing and numerical modelling. Proc. Offshore Technology Conf., Houston, OTC 25978.

Watson, P.G. et al. (14 authors) 2019. Foundation design in offshore carbonate sediments – building on knowledge to address future challenges. Proc. 16th Pan-American Regional Conf. on Soil Mech. and Geot. Eng., Cancun, Mexico.

Wei, Q., Tian, Y., Cassidy, M. J., Gaudin, C. and O'Loughlin, C. 2015. Behaviour of OMNI-Max anchors under chain loading. Proc. 3rd Int. Symp. on Frontiers in Offshore Geotechnics, ISFOG 2015, Oslo, Taylor and Francis, London, 925-930.

Wesselink, B.D., Murff, J.D., Randolph, M.F., Nunez, I.L. and Hyden, A.M. (1988). Analysis of centrifuge model test data from laterally loaded piles in calcareous sand. Engineering for Calcareous Sediments, Balkema, Rotterdam, 1, 261-270.

Wilde, B., Treu, H. and Fulton, T. 2001. Field testing of suction embedded plate anchors. Proc. 11th Int. Offshore and Polar Engng Conf., Stavanger, 544-551.

Won, J.-Y., Audibert, J., Misra, A. and Bush, S. 2018. Hybrid subsea foundation for deepwater FLET: a case history. Proc. Offshore Technology Conf., Houston, OTC 29059.

Wong, P., Gaudin, C., Randolph, M.F., Cassidy, M.J. and Tian, Y. 2012. Performance of suction embedded plate anchors in permanent mooring applications. Proc. 22nd Int. Offshore and Polar Engin. Conf. (ISOPE), Rhodes, ISOPE2012-TPC-0855

Zakeri, A., Clukey, E.C., Kebadze, B., Jeanjean, P., Walker, D., Piercey, G., Templeton, J.S., Connelly, L. and Aubeny, C.P. 2015. Recent advances in soil response modelling for well conductor fatigue analysis and development of new approaches. Proc. Offshore Technology Conf., Houston, OTC 25795.

Zhang, Y. and Andersen, K.A. 2019. Soil reaction curves for monopiles in clay. Marine Structures, 65, 94-113.

Zhang, G., Erbrich, C.T., Finnie, I.M., Neubecker, S.R., White, D.J., Deeks, A.D., Doh, G., Cumming, G. Op den Velde, W., Brown, N. and Little, R. 2015. Geotechnical design and construction aspects of a pipeline-escarpment crossing. Proc. 3rd Int. Symp. on Frontiers in Offshore Geotechnics, ISFOG 2015, Perth, Taylor and Francis, London, 1, 495-500.

Zimmerman, E.H., Smith, M. and Shelton, J.T. 2009. Efficient gravity installed anchor for deepwater mooring. Proc. Offshore Technology Conf., Houston, OTC 20117.