PLATE ANCHORS FOR MOORING FLOATING FACILITIES – A VIEW TOWARDS UNLOCKING COST AND RISK BENEFITS

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Abstract
Optimisation of anchoring technology through improved design or through novel anchor types offers potential cost benefits and risk reduction. This paper makes the case for follower-embedded plate anchors and examines opportunities for refining their current design basis as articulated in design codes to reduce cost and risk. We recast the expression for anchor capacity by separating out uncertainties due to (i) bearing capacity factor, (ii) final embedment depth and (iii) soil strength. This permits sources of uncertainty to be more clearly identified, yielding better strategies for their reduction. Examples described include dynamically embedded plate anchors that self-correct for strength uncertainty, and consolidation-induced increases in the soil strength around the anchor and its connecting mooring chain. Research activities aligned with these opportunities are set out.

1. Introduction

Offshore floating facilities are kept on station using mooring lines that terminate at anchors in the seabed. Mooring lines arrive at the seabed mudline with a load, T_m, and an inclination that is zero for a catenary mooring or greater than zero for a taut mooring (Figure 1). In a catenary mooring a length of mooring chain rests on the seabed, so friction between the seabed and the chain contributes to the overall capacity, reducing the mooring line load at the anchor. This seabed-chain friction continues along the inverse catenary of chain embedded in the seabed. The load experienced by the anchor, T_a, is not only reduced, but is only mobilised when a threshold is exceeded, which may be a large proportion of the design extreme load. In a taut mooring the chain friction is minimal and a static component of load reaches the anchor, as well as cyclic loads over a smaller threshold.

In fine-grained soils, the static and recurrent load seen either by the chain or by the anchor changes the seabed strength over the lifetime of the facility. Initially the strength change is a reduction as pore pressures increase, but intervening periods of low-level or no loading allow these pore pressures to dissipate, allowing the seabed strength to regain (and potentially exceed the initial value). In a taut mooring the strength changes around the anchor could be greatest, whereas in a catenary mooring the chain, which experiences more cycles, may see the most significant effect.

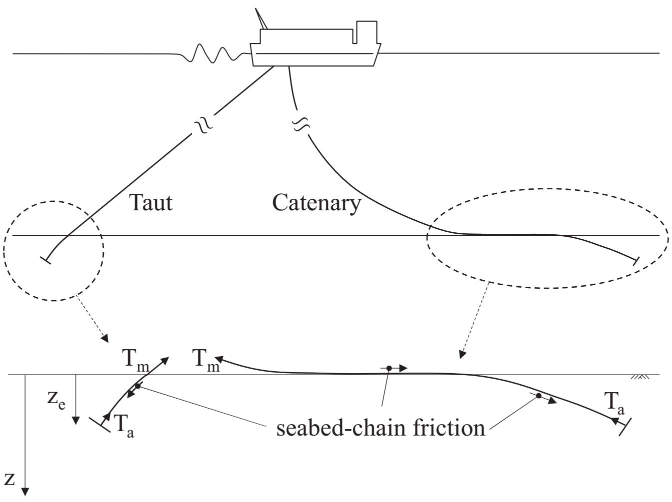


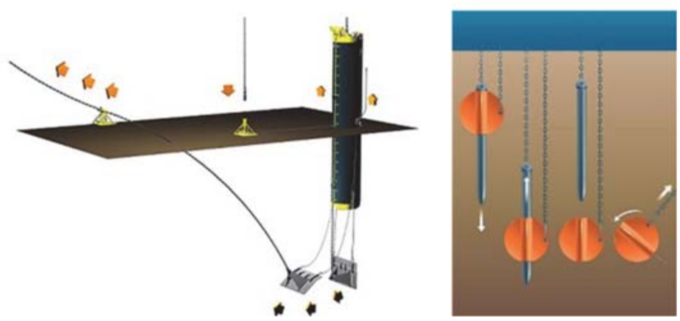
Figure 1: Problem description and notation

These effects, and others, indicate potential value in embracing plate anchors as an alternative to the more established pile anchors (including driven, suction installed and gravity installed). The prize afforded by this opportunity is smaller, cheaper and more reliable anchors. The journey to realising this prize is summarised by the staircase in Figure 2, the steps of which are being tackled within the Australian Research Council Research Hub for Offshore Floating Facilities. This paper firstly articulates the motivation for using plate anchor technology, drawing on available performance data, before then taking the steps of the staircase to identify the incremental advances that are necessary to obtaining the eventual prize.

Figure 2: Staircase towards smaller, cheaper and more reliable plate anchor systems

2. Motivation for plate anchor technology

Anchor types appropriate for deep-water soft soils can be broadly categorised as either piles or plates. Piles include well-established driven and suction-installed piles (or caissons) and the more novel free-fall pile technology. Plate anchors include those that are installed by dragging along the seabed, or are installed using a retrievable follower, e.g. suction embedded plates anchors (SEPLAs; Wilde et al., 2001) and dynamically embedded plate anchors (DEPLAs; O'Loughlin et al., 2014) (see Figure 3). Reuse of the installation follower for the DEPLA and SEPLA leads to cost savings associated with manufacturing and with transporting the anchors to site (as a full anchor spread may be transportable on a single barge).



(a) (b)

Figure 3: Follower embedded plate anchors:
(a) SEPLA, (b) DEPLA

Plate anchor technologies – including the DEPLA and SEPLA – are more efficient (defined as capacity relative to dry mass) at resisting mooring loads as they mobilise the soil in bearing rather than friction (O'Loughlin et al., 2015). This results in significantly smaller and less costly anchors relative to piles. Plate anchor performance relative to the benchmark of suction piles is explored in Figure 4, which compares centrifuge data for plate anchors with unfactored Gulf of Mexico design loads for suction caissons.

SEPLA data are reproduced on Figure 4 from centrifuge model studies reported by Gaudin et al. (2006) and Wong et al. (2012). The former utilised a square plate with side length typical of the shorter side of a rectangular SEPLA. Therefore, the capacity is reduced by up to half compared to a real SEPLA at the same embedment, which typically has a geometrical aspect ratio, B/L = 1.5–2.

The SEPLA centrifuge data by Wong et al. (2012) occupy a relatively wide range of capacity, but include two different anchor scales (the larger having 26% higher bearing area) and relate to tests in which various amounts of consolidation were permitted during the keying process. However, the noteworthy aspect of these test data are that they offer capacities that are as high as the Mad Dog suction caisson design load, highlighting the ability of the SEPLA to satisfy high mooring load requirements.

The DEPLA data on Figure 4 are from centrifuge model tests reported by O'Loughlin et al. (2014). The data show a similar range of capacities to the Wong et al. (2012) SEPLA data, but plot at shallower embedments as the plate is higher on the follower. The scatter in this case is due to significant geometrical differences in the plate. The DEPLA plate area that could be mobilised as bearing resistance differed by a factor of 3.5 across the range of DEPLA geometries tested. The highest DEPLA capacity exceeded the Mad Dog design load and was achieved using a DEPLA that had a combined (follower plus plate) weight that was similar to the Diana caisson. However, the DEPLA plate, which is the load carrying element, weighed only 58% of the caisson, yet provided slightly higher capacity. These results highlight the potential for the DEPLA to also satisfy high mooring load requirements.

It is also instructive to examine the relative efficiency of the anchors, defined as the anchor capacity divided by the dry weight. Reduced scale field data (Blake et al., 2015; O'Loughlin et al., 2016) for practically dimensioned DEPLAs give anchor efficiencies approaching 40 compared with ~7 for the suction caisson design loads on Figure 4. This low efficiency is because suction caissons resist load partly through friction when there is a significant component of uplift at the pad-eye, but also because the depth range over which soil resistance is mobilised extends to the surface, where the strength is lower.

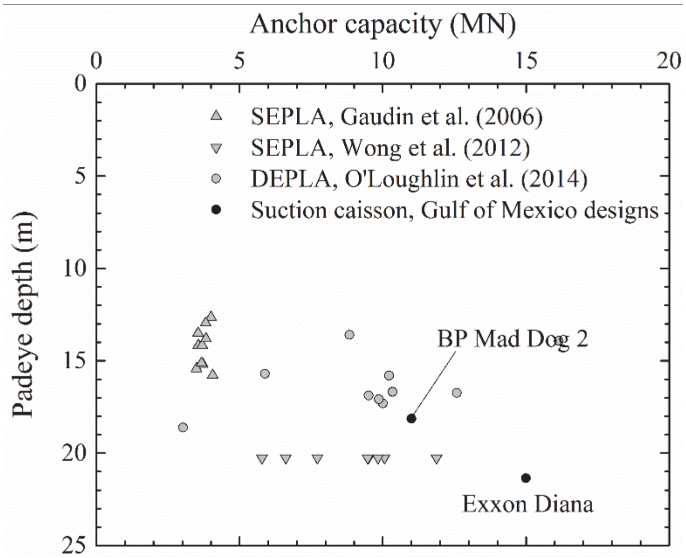


Figure 4: Performance data for plate anchors with suction caisson design examples from Gulf of Mexico

In summary, adoption of the follower-embedded plate anchor technology of SEPLAs and DEPLAs provides an opportunity for cost and schedule savings. These savings are made possible through the much lower anchor size relative to conventional suction caissons, and because the anchors can be deployed from smaller vessels that are more readily available and have lower day rates. However, compared with conventional anchoring technology, the use of follower-embedded plate anchors is relatively immature. SEPLAs have been used for temporary facilities and permanent pre-set moorings, but to the authors' knowledge, not for permanent facilities.

Much of their performance data arises from centrifuge studies (e.g. Gaudin et al., 2006; 2010; Wong et al., 2012), which has led to analytical models that predict the post-installation response and have formed the basis of improvements to the anchor shapes (e.g. Tian et al., 2014). Although the DEPLA has not yet been tested at full scale, there is a large body of high quality performance data from centrifuge and reduced scale field tests (O'Loughlin et al., 2014; Blake et al., 2015; O'Loughlin et al., 2016). In addition, the installation performance of DEPLAs is essentially the same as dynamically installed 'torpedo piles' for which there is much project experience, and the capacity mobilisation performance is very similar to that for SEPLAs (as described previously).

Given the potential of SEPLAs and DEPLAs it is relevant to examine and assess current design codes in view of recent improvements in the knowledge base.

3. Plate anchor capacity assessment

The factored design capacity, Q_{fac}, for undrained loading of a plate anchor is written as (DNV, 2002):

$$Q_{fac} = \frac{1}{\gamma_m} N_c s_u A_p = \frac{1}{\gamma_m}\left(N_{c,strip} s_c\right)\left(s_{u0} \eta U_{cyc}\right) A_p$$

The first expression breaks the response into three fundamental terms (with A_p being the plate area): (1) a resistance factor, γ_m (>1), for uncertainty, (2) a bearing capacity factor, N_c and (3) the undrained strength relevant to the loading, s_u.

The second expression is the approach in DNV (2002), which is shown with brackets that we have added to collect the factors into the fundamental three terms. The bearing capacity factor is composed of the solution for a plane strain strip (varying with depth), adjusted with a shape factor, s_c. The operative strength is the *in situ* value based on laboratory tests, s_{uo}, adjusted for strain-softening and anisotropy, η (= 0.75), and the combined effects of strain rate (U_R) and cyclic loading (U'_{cyc}), through a single factor, U_{cyc}.

The parameters that control each of the three fundamental terms are outlined in Table 1. The following sections address each of the three fundamental terms, identifying uncertainty levels and opportunities for refinement.

Table 1 distinguishes between the parameters or effects that influence N_c and those that affect s_u. Other publications account for effects that alter the operative strength by adjusting N_c. For example, Wong et al. (2012) recommend a reduced N_c to allow for mobilisation effects, including the loss of embedment during keying, and apply this with the *in situ* strength at the as-installed depth. However, our approach is to adhere to the definition of each parameter, namely that s_u is the (volume-averaged) strength of the failing soil and N_c is then the ratio between the mean bearing stress (Q/A_p) and s_u. This approach is supported by the observation that changes in N_c and s_u are independent for surface plate foundations subjected to consolidation: changes in the distribution of s_u do not lead to changes in N_c (Stanier & White, 2017).

Table 1. Plate anchor capacity: sources of uncertainty and opportunities for refinement based on examples and analysis in this paper

Term	Affected by	Typical value	Uncertainty / opportunity	Section
Bearing factor, N_c	Plate shape, thickness, roughness, depth, load inclination	14.5 (beyond z_{crit}/D)	Well-established theoretically, ±5% residual uncertainty	4
Undrained strength, s_u	Loading rate / strain rate	1.25 (typically)	Simplify to a single factor, ~1 (via penetrometer-based s_u)	5
	Strain softening	$\eta = 0.75$		
	Consolidation under sustained load Softening from undrained cyclic load Reconsolidation after cyclic load	- not considered - typically 0.7 - not considered	Up to +20–50% increase - Up to +40–100% increase	6
	Change in embedment under loading - Loss of embedment during keying - Gain in embedment by diving	 - typically -5% - not considered	 - Up to +30–150% increase	9
Resistance factor, γ_m	Soil variability / uncertainty, target reliability	1.4	DEPLA: ~20–25% reduction for depth self-correction	7

4. Plate anchor bearing capacity factors

Numerous numerical and analytical studies have considered the bearing capacity factor of buried plates. Collectively these studies show that the anchor capacity factor, N_c, is controlled by anchor geometry, roughness, load inclination, embedment depth and whether soil is assumed to remain attached to the base of the plate (flow-around) or is assumed to detach. The latter assumption creates the largest difference in the capacity factor but the potential for soil breakaway at the base of a deeply buried plate is unlikely. The displacement rates required for a plate to generate undrained behaviour are too high for pore water to seep into a potential gap at the underside of the plate. Hence for a deeply buried plate it is appropriate to assume that the soil remains attached.

Figure 5 shows the trend with depth of definitive numerically-derived values of N_c for rectangular (L/B = 2) (N_c = 13.76) and square (N_c = 14.15) plate anchors, circular (N_c = 14.35) plates and the DEPLA that features two orthogonal circular plates (N_c = 14.9; Wang & O'Loughlin, 2014), using a realistic value of thickness t/B = 0.03. Beyond a critical depth of z_{crit}/B (or z_{crit}/D) = ~2, the bearing factor can be simplified as N_c = 14.5 with the definitive numerical solutions lying within ±5% for all shapes.

The DNV (2002) approach for a square plate (Ancestries) is in close agreement at depth, but is conservative at shallow depths.

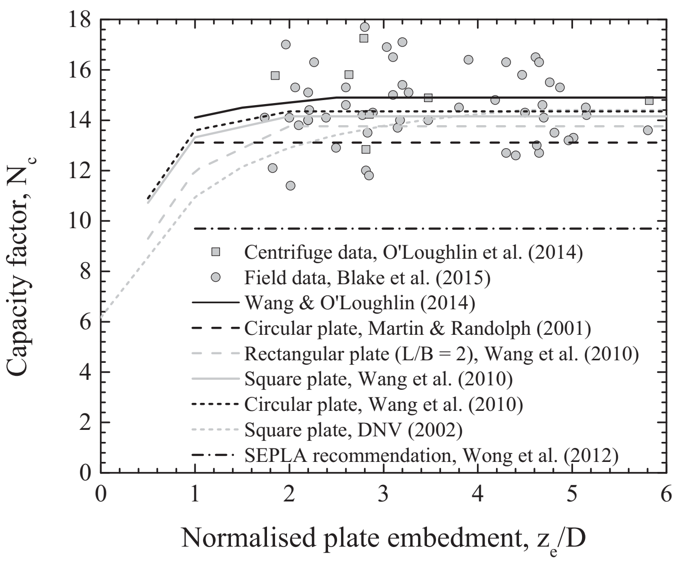


Figure 5: Experimental DEPLA capacity factors compared with relevant numerical, analytical and recommended values

The classical solution for an infinitely thin rough circular plate (N_c = 13.11; Martin & Randolph, 2001) shows that the finite thickness of a real anchor has a small (10%) effect. The surface roughness has a similar minor influence.

Confirmation of these theoretical and numerical values is provided by the large database of back-analysed N_c values from centrifuge and reduced scale field tests of circular DEPLAs shown by markers on Figure 5, which has a mean of $N_c = 15.1$. The scatter in the experimentally derived capacity factors originates from the inevitable uncertainty in soil strength (which in design is accounted for via γ_m). In these cases, s_u was derived from penetrometer tests (see Section 5).

5. Operative strength: rate and softening effects

The methodology set out in DNV (2002) includes separate multiplicative corrections to soil strength related to (i) the difference in strain rate and (ii) the progressive failure and strain softening around the anchor, compared to the laboratory element tests used to derive s_u. The recommended strain rate correction is $\eta = 0.75$, and the rate effect, $U_r \sim 1.25$ typically. Multiplied together, these approximately cancel.

A similar cancellation of rate and strain softening effects underpins the similarity between s_u values derived from flow-round penetrometer tests (T-bar and ball) and from laboratory element tests when the theoretical bearing factor from plasticity limit analysis is used (Einav & Randolph, 2005; Low et al., 2010), as illustrated in Figure 6.

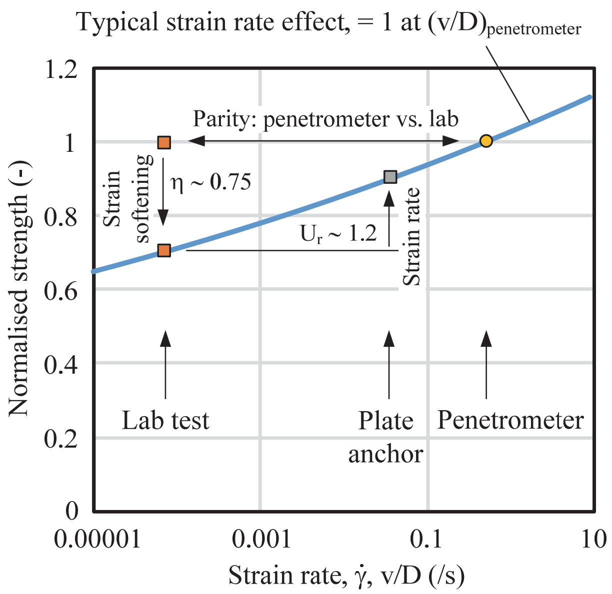


Figure 6: Strain rate and strain softening effects on lab and penetrometer shear strengths relative to plate anchor capacity

Figure 6 also shows that the strain rate around a plate anchor loaded to failure is similar to a penetrometer test. Given that these objects have approximately the same shape, the progressive failure aspect is also similar. This explains why centrifuge and field studies of plate anchor capacity show excellent agreement between predicted and observed anchor capacity when using strength values derived using $N_{T\text{-bar}} = 10.5$ and making no further adjustments for strain rate or softening (O'Loughlin et al., 2016).

It may therefore be preferable to scale directly from penetrometer to plate anchor, using theoretical bearing factors in each case. This eliminates any major adjustments for strain rate and softening. Regardless of whether the soil strength is derived from laboratory element tests or *in situ* penetrometer tests, some allowance may be warranted due to strain rate effects, and established formulations to model this are described in DNV (2002) and have been validated by both soil element tests (e.g. Rattley et al., 2010) and multi-rate penetrometer tests (e.g. Chow et al., 2017).

6. Operative strength: consolidation from sustained and cyclic loading

For typical soft clay conditions considered in this paper, consolidation will occur around a plate anchor and its connecting mooring chain within a period of months, rather than the decades relevant to a gravity-based structure, due to their relative size. For this reason, some level of consolidation-induced strength gain may occur before the design load event.

Simple relationships have been established for the gain in capacity of a surface foundation subjected to consolidation under sustained load (Gourvenec et al., 2014). For typical soft clay parameters, the long-term gain in capacity (in percent) is approximately equal to the sustained load level expressed as a percentage of the initial capacity. Considering the typical range of sustained tensions on plate anchors, a gain in capacity of 20–50% might be attained. Whether the Gourvenec et al. (2014) approach requires adjusting for plate anchors in tension requires confirmation. For plates under sustained compression, the method works well (Vulpe & White, 2014).

Cyclic loading causes a build-up of pore pressure within the soil surrounding a plate anchor. To determine the resulting reduction in strength, pore pressure accumulation methods are well-established (e.g. Andersen & Lauritzen, 1988). The DNV (2002) code recommends applying these methods by equating the anchor load (as a fraction of the monotonic capacity) to a shear stress level (relative to the monotonic strength) in a soil element test. By this approach, a time history of anchor loads representing a design seastate can be binned and accumulated to determine the reduction factor on anchor capacity due to cyclic loading, known as U_{cy}.

This reduction factor, U_{cy}, is related to a single event or seastate. Any pore pressure build up at the anchor leads to outwards drainage afterwards, meaning a reduction in voids ratio and hence a gain in strength. This leads to the possibility to bank gains in strength and capacity through episodes of loading and dissipation. This mode of strength gain is already codified in practice for assessing axial pipeline friction (Atkins 2015; White et al., 2015) and a long-term gain in sliding capacity by a factor of 2–3 is typical. For sliding foundations, the same behaviour is observed in model tests and numerical analysis (Cocjin et al., 2014; 2017; Feng & Gourvenec, 2015).

For buried plate anchors, the maximum potential gain in capacity from episodes of loading and consolidation can be estimated in the same way as for sliding surface foundations. The undrained strength can transition from a contractile response, to a response at the critical state, in which the shear-induced pore pressure in the failing soil is zero. Typically, this might lead to a doubling (i.e. 100% increase) in strength.

To quantify this progressive gain in strength, a cycle-by-cycle critical-state type model could be used (e.g. following Cocjin et al., 2017 for shallow foundations subjected to pipeline startup and shutdown loads). However, for plate anchors subjected to wave period loading (i.e. ~10^6–10^8 cycles in the design life) it is more practical to discretise the loading history by seastate not individual waves. White et al. (2017) describe an approach to achieve this by extending conventional (e.g. DNV, 2002) cyclic strength degradation methods.

In summary, consolidation effects during monotonic loading and following cyclic loading can create additional plate anchor capacity within time periods that are of practical relevance. Calculation methods are emerging to capture these changes in capacity via 'whole life' modelling of the loading and capacity histories. These methods, applied in a probabilistic way, are important if consolidation effects are to be 'banked', particularly to provide a reliability-based answer to the question 'what if the design load occurs during a storm in the first week of operation?'

7. Capacity uncertainty: DEPLA self-correction

Installation of a plate anchor using a dynamically-penetrating follower has advantages of speed and simplicity (O'Loughlin et al., 2015). There is an additional advantage related to a 'self-correction' of the installed embedment that compensates for uncertainty in the soil strength profile. If the soil strength is lower than the characteristic design value (which might be a P_{10} low estimate, for example), the anchor will penetrate deeper than expected. This means it enters stronger soil, which compensates for the strength being lower than the design value.

This effect means that the same reliability (or probability of failure) is attained when using a lower resistance factor, γ_m, applied to a DEPLA compared to the same size of plate installed to a specified depth.

The example shown in Figure 7 is used to illustrate this point, via a simple Monte Carlo analysis of the dynamic embedment behaviour allowing for soil strength uncertainty. The strength is proportional to the depth below mudline with a mean (expected) value of 1.25 kPa/m. The uncertainty is normally distributed with a standard deviation of 0.19 kPa/m.

The design factored capacity of Q_{fac} = 500 tonnes (5 MN) is achieved by a 24m^2 SEPLA installed to 20m depth, using the LE (P_{10}) strength profile (1.0 kPa/m) and a resistance factor of γ_m = 1.4. This results in a probability of failure, P_f, of 2.6×10^{-3} (considering only the uncertainty on resistance not load). Failure only occurs if the strength is as low as 0.72 kPa/m (which has a likelihood of 2.6×10^{-3}). In contrast, the same probability of failure can be achieved using a smaller DEPLA (18.7m^2) designed to reach the same embedment (20m) under the P_{10} (LE) strength.

The smaller anchor is permissible because if the strength gradient lies below the LE (P_{10}) value, an increase in embedment will compensate. As a result, a lower resistance factor attains the same reliability, which in this case is γ_m = 1.09. This is a 22% reduction on the value of γ_m = 1.4 used for the SEPLA, which results in the 22% reduction in the required plate area. Alternatively, the same plate area could be used for the DEPLA as the SEPLA, but designed for a shallower embedment under the P_{10} strength, reducing the required follower size. The same outcome applies regardless of the choice of characteristic soil strength (P_{10}, P_{50} etc.).

In summary, to achieve the same reliability, dynamically-installed anchors require a lower resistance factor compared to anchors installed to a specified embedment, because the dynamic embedment process 'self-corrects' for soil strength uncertainty.

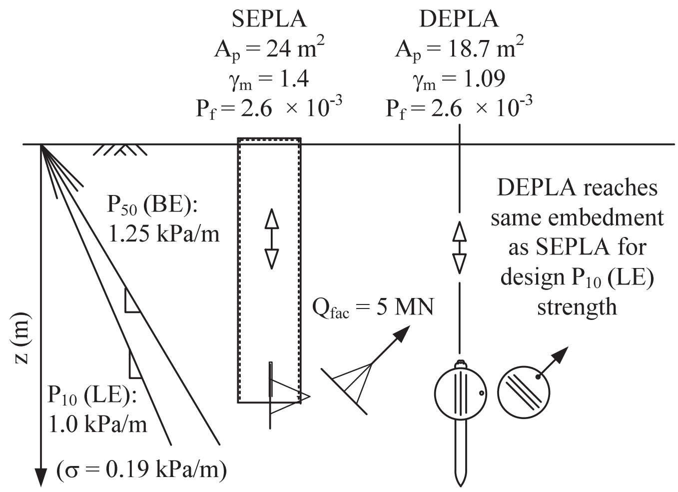


Figure 7: Example used to illustrate that the dynamic embedment of a DEPLA 'self-corrects' for soil strength uncertainty

8. Chain-seabed interaction

To demonstrate the load contribution from the embedded section of the mooring chain, analyses were conducted of an embedded mooring chain with a bar diameter of 175mm, terminating at a suction caisson at a padeye depth of 13.7m and a DEPLA at a padeye depth of 27.3m. The analyses consider a catenary mooring with a 100t preload applied after installation, horizontally at mudline, 100m away from the anchor, and apply typical chain-soil interaction parameters. The geometry and padeye embedment depth were calculated to satisfy an unfactored 5 MN mooring line load arriving at the anchor padeye at 45° (assumed *a priori*) for a seabed strength, $s_u = 1z$.

Figure 8 shows the chain movement and the corresponding chain load at the anchor padeye and at the mudline, a distance x = 500m from the anchor. The load contribution from the chain represents an additional 1–1.5 MN of mooring load for the DEPLA, which is double the chain load contribution for the shallower suction caisson. Given that this chain load represents 30% of the design load, the DEPLA could be shallower and/or smaller whilst still providing adequate capacity. However, the deeper DEPLA padeye leads to a chain slack of 7.5m at the design load of 5 MN compared to 2m for the suction caisson.

Accounting for the load contribution of the chain allows for shallower anchors, which would reduce the level of chain slack. However, in practice this higher level of chain slack associated with the plate anchors may be tolerated by the mooring system, depending on the mooring dynamics and the capacity to re-tension the mooring lines in service.

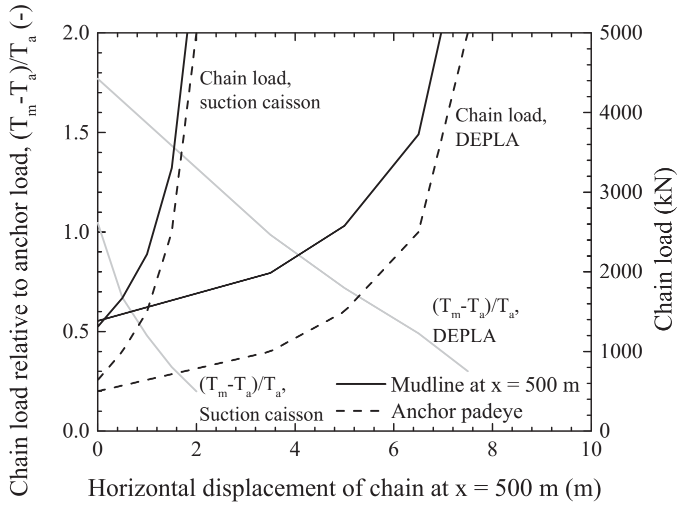


Figure 8: Comparison in the chain load contribution and the associated chain slack for a DEPLA and suction caisson designed for a 5MN anchor load

The reduction in chain tension following the design load results in a reversal in the chain mobilisation, so a component of the load transferred to the anchor is maintained (Frankenmolen et al., 2016). The chain analyses in Figure 8 indicate that this will be approximately 20% of the design load. Consolidation due to this load will increase soil strength, as discussed earlier in the paper. Indeed, calmer periods between storm events will allow for strength increases in the soil surrounding the chain, which will increase the potential load contribution from the chain.

A further differentiator in the chain analyses for the suction caisson and the plate anchor is the response to load inclination at the padeye. A key design consideration for the suction caisson is the uplift load at the padeye, which is governed by the extent to which the chain cuts through the seabed. This is of much lower importance for plate anchors as capacity is relatively independent of chain inclination. For instance, numerical analyses reported by Wang & O'Loughlin (2014) for a DEPLA show that N_c reduces by only 3.4% at z_e/D = 2 as the load inclination changes from vertical to 45°, with no reduction at z_e/D = 4.

9. Plate anchor geometry optimisation

As noted by the design codes, keying of a plate anchor during loading – when it rotates to face the applied load – is generally associated with a loss in embedment and this loss in embedment should be considered when selecting the value of s_u to calculate plate anchor capacity, rather than reducing the anchor capacity factor, N_c. For typical plate anchor geometries, the loss in embedment during keying may be taken as less than 0.5 times the plate width (e.g. Wang et al., 2011). This is lower than values reported from centrifuge studies that involved keying under vertical loading, and reflects the more realistic load inclinations arising from the inverse catenary of the embedded mooring chain. This loss of embedment corresponds to a reduction in s_u by about 5% (1.3 kPa) for the SEPLA MODU design scenario considered in O'Loughlin et al. (2015), which is the same level of uncertainty associated with the *in situ* measurement of s_u from penetrometer tests (Peuchen & Terwindt, 2014).

Furthermore, an emerging body of work (e.g. Tian et al., 2014) shows the potential for the plate anchor design to be optimised such that the plate anchor dives deeper in the seabed when overloaded. This provides for an increase in s_u and hence anchor capacity, provided that gross anchor movements can be tolerated. An example is provided in Figure 9, which shows that the current SEPLA design could be optimised by offsetting the load attachment point (parallel to the plate), leading to an overloaded anchor capacity that is ~2.5 times higher than the non-overloaded capacity of the standard design.

Further optimisation may be achieved by using wire or synthetic rope rather than chain in the embedded section of the mooring as the lower diameter rope cuts through the seabed more readily than the chain. This allows the chain slack to be taken up at more moderate loads, e.g. at load levels achievable using the bollard pull of an anchor handling vessel and flattens the angle of the mooring line at the pad-eye. However, consideration would need to be given to the integrity of the rope over the lifetime of the mooring.

10. Concluding remarks

In summary, current design requirements for plate anchors appear overly conservative and are a barrier to the uptake of this promising technology. This paper has explored the origins of this conservatism and has identified (through the steps of the staircase in Figure 2), opportunities for reducing uncertainty and refining embedded plate anchor design.

If the design requires an anchor that does not move in the seabed, the opportunities are lower uncertainty through self-correcting dynamic embedment and consolidation-induced seabed strength gains, which from Table 1, allow for up to 125% improvement. If gross movement of the anchor is permitted, consolidation induced strength changes do not apply, but are eclipsed by the higher strength mobilised if the anchor is designed to dive when overloaded, which can lead to an overall improvement of up to 150%.

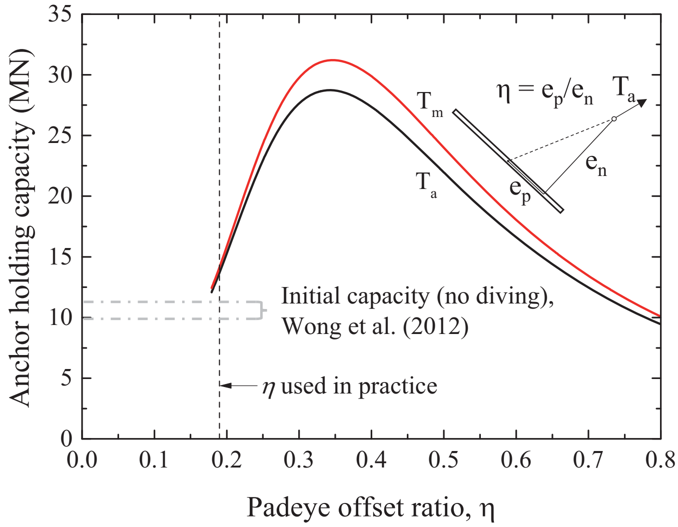


Figure 9: Effect of varying the load attachment point on a SEPLA (after Tian et al. 2015)

11. Acknowledgements

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