Multiline Ring Anchor system for floating offshore wind turbines

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Abstract. The trends in the offshore wind industry have shown floating offshore wind turbines (FOWTs) technology and installation in deep waters due to stronger, more consistent wind resources and mitigation of aesthetic issues. Nevertheless, the high capital cost of the support systems remains a primary obstacle. Thus, this study presents a novel, integrated, and networked multiline ring anchor (MRA) system for FOWTs that can provide significant capital cost savings. Other attractive features of the anchor include versatility in regard to the range of soil conditions in which it can be deployed, relatively high geotechnical efficiency, capability for precise positioning and a deep embedment which provides for robust performance under unintended torsional loading. A limited comparative study of the MRA to a suction caisson anchor in soft clay shows the MRA to be clearly more efficient under horizontal loading, but only a marginally better under vertical loading. Incorporating keying flaps in the design has promise for eliminating the latter performance issue.

1. Introduction

An estimated 60% of potentially exploitable offshore wind energy in the United States occurs at water depths beyond that practical for fixed foundations, leading to a need for cost-effective floating offshore wind turbine (FOWT) systems. As foundations comprise a significant portion of overall costs, efficient anchor and mooring system design are needed to make FOWT systems economically competitive. The development of anchors for mooring FOWTs should be guided by the following considerations:

Cost. Costs can be contained by minimizing the number of required anchors in the system, maximizing geotechnical efficiency (load capacity $F$/weight $W$) of the anchors, and minimizing installation costs. Multiline anchors, capable of securing more than one mooring line to a single anchor permit substantial reductions in the total number of anchors [1]. Fontana et al. [2] show that load demand on a multiline anchor does not differ substantially from that of its single line counterpart. Since anchor load capacity is proportional to the strength or effective stress levels in surrounding soils, deep embedment is the key to achieving high geotechnical efficiency [3, 4]. Fewer and lighter anchors lead to reduced costs for anchor materials, transport, and installation [5].

Soil conditions. Utilizing anchors that are deployable in the wide range of soil conditions (soft-to-stiff clay, sand, stratified) typical of many potential wind farm sites. While deep embedment is possible for most anchor types in soft clay, deep embedment in sand and stiff clays is uncertain or not possible for many anchor types [1]. This limitation is most problematic when anchors must resist vertical load demand since deep embedment is key developing resistance to uplift.
Reliability. Performance under unintended loading conditions, e.g. torsional load demand due to partial mooring system failure, is a key aspect of reliability, which improves with increasing anchor embedment depth [3, 4]. The ability to precisely position an anchor also improves reliability. Since anchor embedment depth is a major factor influencing anchor load capacity, precise positioning leads to more reliable predictions. This paper first presents a novel anchor, the multiline ring anchor (MRA), developed to address the considerations discussed above. Then, the overall capabilities of the MRA are contrasted against conventional anchors. Finally, a cost comparison is made for the MRA and a conventional suction caisson in soft clay for a selected base case analysis. Dimensioning of the two anchors for the cost comparison is based on plastic limit analyses utilizing a virtual work least upper bound approach [6].

2. The Multiline Ring Anchor (MRA)

2.1. The concept of the MRA

The MRA (patent-pending) includes an embedded ring with up to six mooring lines which can be attached. Optional wing plates or keying flaps can also be attached around the ring anchor to enhance horizontal and vertical load capacity (Figure 2). This concept is expected to extend its applications beyond offshore wind energy to include the oil and gas industries, wave and tidal energy. The installation procedure of the MRA is as follows: the anchor is installed by attaching it to the end of a pile and penetrating it to an adequate embedment depth using suction installation or conventional driving. The pile is then extracted, leaving the ring anchor in a certain place (Figure 3).

![Figure 1. Comparison between single line anchor and multiline anchor [2]: (a) layout of single line anchor, (b) layout of 3-line anchor, (c) multiline anchor concept.](image1)

![Figure 2. Strategies for enhancing load capacity: (a) keying flaps, (b) wing plates.](image2)

![Figure 3. The installation procedure of the MRA.](image3)
2.2. Potential advantages of the MRA

The advantages of the MRA can perhaps be best illustrated through comparison to existing anchor alternatives. The alternatives [6] considered include driven piles, suction caissons, drag anchors, dynamically installed piles (DIPs), dynamically embedded plate anchors (DEPLAs), pile driven plate anchors (PDPAs), suction embedded plate anchors (SEPLAs). Selection of a suitable anchor type may be considered two proceed at two levels. The first is a basic screening tool based on soil conditions and load demand on the anchor. In catenary mooring systems, the load applied on the anchor is nearly horizontal, in which case deep embedment of the anchor is not strictly necessary. By contrast, taut and semi-taut mooring systems impose a vertical load demand on the anchor, the development of which requires deep embedment into the seabed. If seabed soil conditions are such that deep embedment of a given anchor is not possible and if vertical load capacity is needed (Table 1), then the anchor under consideration must be eliminated from further consideration, irrespective of any cost considerations. As Table 1 shows, deep embedment is feasible in soft clays; therefore, all anchor types are potentially suitable. Thus, the following points apply:

- For soft clay conditions, any anchor type is potentially suitable for (1) catenary mooring systems or (2) any mooring system.
- In seabed soil conditions other than soft clay, the list of possible anchor types reduces to driven piles, suction caissons, pile driven plate anchors and the MRA.
- The use of suction caissons in sands is conditional. The low aspect ratio (length of suction caisson $h/\text{diameter of suction caisson } D$) necessary for suction installation usually limits the vertical load capacity to short-term loading, where the diameter must be sufficiently large, the sand must have sufficiently low permeability, and the loads must be of sufficiently short duration. There are certain situations where these conditions can be satisfied, but this limitation becomes a factor when comparing suction caissons to the MRA that do not have this limitation.
- Suction installation in stratified soils will usually require a short aspect ratio (as described above for sands) as well as difficulty in installation. Recently, great strides have been made in installing suction caissons in stratified soils through procedures such as cycling and jetting. Nevertheless, the added effort in planning such operations as well as the increased risk of failed installations reduces the attractiveness of suction caissons as an alternative.

Table 1. Capability for developing vertical load capacity for various soil conditions [6]

| Soil condition | Anchor Type | Driven piles | Suction caissons | Drag anchors | DIP | DEPLA | PDPA | SEPLA | MRA |
|----------------|-------------|--------------|-----------------|--------------|-----|-------|------|-------|-----|
| Soft clay      | yes         | yes          | yes             | yes          | yes | yes   | yes  | yes   | yes |
| Stiff clay     | yes         | yes          | no              | no           | no  | yes   | no   | yes   | yes |
| Sand           | yes         | yes$^a$      | no              | no           | no  | yes   | no   | yes   | yes |
| Stratified     | yes         | yes$^{a,b}$  | no              | no           | no  | yes   | no   | yes   | yes |

$^a$ for short-term loading only
$^b$ installation not always feasible

After initial screening of the various anchor alternatives based on soil conditions and load demand, the remaining alternatives can be evaluated based on factors related to cost and reliability (Table 2). Since costs are site-specific, the discussion that follows involve qualitative cost comparisons simply to illustrate the potential merits of the MRA.

Multiline potential is an obvious cost factor, since it permits a reduced number of anchors with concomitant cost reductions in geotechnical site characterization, material, fabrication, transport and installation. In general, the axial symmetry of tubular anchors (piles, caissons, PDPAs and MRA)
renders them well-suited to multiline mooring systems. By contrast, plate anchors do not provide a geometry suitable to simple multiline attachments.

Geotechnical efficiency clearly impacts the costs for anchor materials, fabrication, transport and handling. In general, plate anchors typically have high efficiency (say, load capacity $F/\text{weight } W > 40$), since they derive their load capacity from bearing resistance. When they are deeply embedded, their efficiency is better yet, since their bulk is concentrated at depth, where the soil is strongest. By contrast, piles and caissons derive much of their load capacity from friction, which is relatively inefficient. Additionally, much of their bulk is contained within weak, shallow soils that contribute little to load capacity. For these reasons, piles and caissons are considered here to have low efficiency, say $F/\text{weight } W < 20$. Dynamically installed (torpedo) piles deeply embed, which gives them an advantage on efficiency, but they are necessarily heavy to achieve deep penetration. Therefore, they are assigned a medium efficiency. The MRA relies to some extent on friction, which is an inefficient mechanism for mobilizing load capacity. However, this is offset by its deep embedment in strong soils. Thus, the MRA has an efficiency that is somewhat less than most plate anchors, but still well above piles and caissons.

Installation costs are least for anchors installed by dynamic installation (DIP, DEPLA) or drag embedment. At the high end of costs are anchors that require a jack-up rig or vessel to support installation, driven piles and pile driven plate anchors. Intermediate are methods involving suction installation, which can be relatively time consuming (close to a day per anchor) but do not require much beyond a remotely operated vessel (ROV) to conduct the pumping. These anchors include suction caissons and SEPLAs. Depending on soil conditions the MRA can be installed by either suction or driving, so Table 2 assigns it a medium-high installation cost.

The last two consideration, precise positioning and torsional resistance largely relate to reliability. Driving and suction installation is usually precisely controlled, so anchors installed by these methods enjoy high reliability in regard to position and, concomitantly, the reliability of the ultimate load capacity prediction, which depends heavily on embedment depth. By contrast, dynamic installation and drag installation involve significant uncertainty in embedment depth and, consequently, load capacity. It is noted that not only does this affect reliability, it will likely lead to increasing installation costs due to a need for proof load testing. In regard to unintended loading, deeply embedded anchors may lose some capacity (say 10%) due to torsional load demand, but otherwise function well. As Table 2 shows, most anchors can be expected to perform acceptably. The major exceptions are shallowly embedded drag anchors (typically in sand or stiff clay), which exhibit minimal resistance to out-of-plane (torsional) loading.

### Table 2. Relative capabilities of various anchor types [6]

| Factor                  | Driven piles | Suction caissons | Drag anchors | DIP | DEPLA | PDPA | SEPLA | MRA |
|-------------------------|--------------|------------------|--------------|-----|-------|------|-------|-----|
| Multiline potential     | yes          | yes              | no           | no  | no    | no   | no    | yes |
| Geotech. Efficiency     | low          | low              | high         | medium | high | high | high | medium, high |
| Installation cost       | high         | medium            | low          | low | low | high | medium | medium, high |
| Precise position        | yes          | yes              | no           | no  | no    | yes  | yes | yes |
| Torsional resistance    | yes          | yes              | no\(^a\)     | yes | yes | yes | yes | yes |

\(^a\) except for deep embedment in soft clay
3. Example comparative study
In evaluating the load capacity of the MRA, comparison to conventional suction caisson anchors can be instructive. As a basis for comparison, this study considers a 3-m diameter by 15-m long caisson in soft clay. The analyses will show that a caisson this size will have an ultimate load capacity of about 8,000-10,000 kN. This base case comparison is not linked to a specific wind turbine. However, for perspective, Fontana et al. [2] predict a survival case load demand of about 3,800 kN for a 5 MW-offshore wind turbine. Thus, the particular anchor chosen for the comparison corresponds to a relatively high capacity anchor. The soil profile has a typical soft clay (e.g. Gulf of Mexico, [7]) soil strength with an undrained shear strength at the seabed \(s_{um} = 5\text{kPa}\) and linear strength gradient \(k = 2\text{kPa/m}\). A soil-pile adhesion factor of 0.7 was used in this analysis. The study will consider (1) a conventional suction caisson and (2) an MRA designed to provide load capacity equal to that of the suction caisson. The base case is a suction caisson having diameter \(D = 3\text{m}\), length \(h = 15\text{m}\), and wall thickness \(t_w = 0.04\text{m}\).

The MRA load capacity parity can be achieved either by increasing the MRA diameter or adding wing plates. The design procedure adopted in this study is to (1) evaluate the MRA capacity using the same diameter as the suction caisson, (2) add wing plates to a maximum dimension \(L_w = D/2\), and (3) if the previous step does not produce the target load capacity, incrementally increase \(D\). Since both the types of anchors have multiline capabilities, the MRA has no comparative advantage from this perspective. Therefore, the comparison will focus on the anchor weight and size needed to provide comparable load capacity. The MRA is assigned the same tip embedment depth, diameter, and wall thicknesses, in addition to an aspect ratio \(L/D = 5/3\).

![Figure 4. Suction caisson and MRA in clay (Suction caisson selected for the study has the same diameter and three times of the length of the MRA to compare the load capacity).](image)

![Figure 5. Examples of the projected area of the MRA: (a) no wing, (b) 4 wings, (c) 6 wings](image)
3.1. Load capacity comparisons

The load capacity analysis for the conventional caisson is estimated using a plastic limit analysis described by Aubeny [6]. Analysis of the MRA requires some modification from the conventional caisson analysis. Firstly, there is no resistance at both the top and the bottom of the anchor. Therefore, the formulation for lateral-moment resistance at the bottom of the caisson described by Aubeny [6] is also applied at the top. This does not quite double the end resistance, since the soil strength at the top of the anchor is lower than that at the bottom due to the strength gradient $k$. Secondly, the bearing resistance from the wings needs to be added to the overall lateral resistance. Quantifying this mechanism of resistance is a matter of ongoing research. However, based on centrifuge tests in clay on anchors having similar geometry to the MRA, Bang et al [8] concludes that taking the projected area $A_p$ of the cylinder-wing plate system provides reasonable estimates of lateral capacity, so this procedure was adopted in the present study. The projected area is a function of number of wing plates, the width of wing plates, and load angles (Figure 5). The adopted bearing factor $N_p = P_{ult}/s_u D$, where $P_{ult}$ is ultimate lateral load capacity per unit depth and $s_u$ is undrained shear strength) is about 11.4. Preliminary findings from rigorous numerical study on the effects of wing plates currently in progress show this value of $N_p$ to be slightly conservative.

The comparative study presented herein is for pure horizontal and pure vertical loading, $H_{max}$ and $V_{max}$. The former is more or less indicative of anchor performance for catenary mooring systems. Taut and semi-taut mooring systems actually involve combined horizontal-vertical loading, but $V_{max}$ is nevertheless a good metric of anchor performance as it exerts a major influence on load capacity under inclined loads. For the purpose of evaluating $V_{max}$, a reverse end bearing factor $N_{rb} = 9$ is used in conventional suction caisson calculations [6]. For the MRA, $V_{max}$ is computed assumed an annular tip resistance factors $N_t = 9$ for the ring, and plate end bearing factors $N_p = 7.5$ for the internal stiffeners and wing plates [6]. Bearing resistance is assumed to mobilize at the top and reverse end bearing resistance is assumed at the bottom of all anchors components.

Figure 6a shows the predicted relationship between horizontal load capacity $H$ and load attachment depth $L$ for a conventional suction caisson, an MRA without wing plates, and an MRA with wing plates. The maximum horizontal load capacity $H_{max}$ corresponding to an optimal load attachment depth is used as a basis of comparison. Since both anchors have this limitation, it is not considered to affect the relative comparison of the two anchors. As the MRA has the same diameter as the caisson, Figure 6a shows its capacity is predictably substantially reduced when the top two-thirds of the tube is removed. However, with the wing plates added as detailed in Table 3, the MRA achieves parity in horizontal load capacity with the suction caisson. In this case, parity was achievable without a need to increase $D$.

Suction anchors, including the MRA, are designed to maximize lateral load capacity by minimizing rotation, or equivalently moment load demand, on the anchor. Accordingly, selecting an optimal mooring line attachment depth $L_{opt}$ that minimizes rotation serves to maximize horizontal load capacity $H$, as shown in Figure 6a. Since $L_{opt}$ is affected by the soil strength profile [6] and since the soil strength is seldom known with certainty, it follows that the design estimate of $L_{opt}$ may be inaccurate. Figure 6a shows how inaccuracy in $L_{opt}$ can affect load capacity $H$. Due to its shorter length, the MRA actually has less moment resistance than a conventional caisson, with correspondingly greater reduction in $H$ for a given level of deviation of $L_i$ from the true $L_{opt}$. The sensitivity of horizontal load capacity to unintended moment loading can alternatively be expressed by transforming the $H-L_i$ profiles in Figure 6a into the ultimate force-moment interaction diagram shown in Figure 6b, where moment is defined as $M = H |L_i - L_{opt}|$. This figure shows the conventional caisson to have about twice the moment capacity as that of an MRA. However, barring the possibility of an extremely poor design estimate of $L_{opt}$ (for example, $|L_i - L_{opt}| > 1$ m) the likelihood of a moment-rotation failure for an MRA is small. Thus, while uncertainty in $L_{opt}$ may warrant the use of a larger safety factor in horizontal load capacity calculations for the MRA, the likelihood of a moment failure is relatively small.
Table 3 also shows the results of repeating the design procedure outlined above for the case of vertical load capacity. In this case, in addition to adding wing plates, the MRA diameter needed to be increased to $D = 4\text{ m}$ to achieve parity in vertical load capacity with the suction caisson.

**Table 3.** Comparative evaluation of suction caisson and MRA load capacity

| Anchor                  | Features                | Capacity enhancement | Weight (kN) | $H_{\text{max}}$ (kN) | $V_{\text{max}}$ (kN) |
|-------------------------|-------------------------|----------------------|-------------|------------------------|------------------------|
| Suction caisson         | $D = 3\text{ m}$       | --                   | 557         | 9,960                  | 5,130                  |
|                         | $L = 15\text{ m}$      |                      |             |                        |                        |
|                         | $t = 0.04\text{ m}$    |                      |             |                        |                        |
| MRA matching horizontal capacity | $D = 3.3\text{ m}$     | 6 wing plates:       | 350         | 10,800                 | --                     |
|                         | $L = 5.5\text{ m}$    | $W_{w} = 1.65\text{ m}$ |            |                        |                        |
|                         | $z_{\text{tip}} = 15\text{ m}$ | $L_{w} = 5.5\text{ m}$ |            |                        |                        |
|                         | $t = 0.04\text{ m}$   | $t_{w} = 0.04\text{ m}$ |            |                        |                        |
| MRA matching vertical capacity | $D = 4\text{ m}$     | 6 wing plates        | 538         | --                     | 5,250                  |
|                         | $L = 6.67\text{ m}$   | 3 stiffeners:        |             |                        |                        |
|                         | $z_{\text{tip}} = 15\text{ m}$ | $L_{s} = 6.67\text{ m}$ |            |                        |                        |
|                         | $t = 0.04\text{ m}$   | $t_{w} = 0.04\text{ m}$ |            |                        |                        |

3.2. **Comparative efficiency**

In terms of geotechnical efficiency under horizontal loading, $\eta_{H} = H_{\text{max}}/W$, the suction caisson’s efficiency is $\eta_{H} = 17.9$, versus an MRA efficiency $\eta_{H} = 29$. Thus, the MRA has a clear advantage in efficiency in regard to horizontal load capacity. By contrast, the vertical load efficiency of the MRA, $\eta_{V} = V_{\text{max}}/W = 9.8$, is only marginally greater than that of a suction caisson ($\eta_{V} = 9.2$), even when the MRA diameter is increased and wing plates are added. A primary reason for this is that a suction caisson subjected to short-term vertical loading enjoys the benefit of reverse end bearing resistance across the entire bottom cross-sectional area, a benefit which is lost when the top two-thirds of the tube are removed to create the MRA. This issue was recognized in the original development of the MRA and it was a primary motivator for introducing the keying flap feature shown in Figure 2. The effectiveness of the keying flap is a matter of future needed research. It should be emphasized that relatively minor improvement in vertical load efficiency offered by the MRA over suction caissons in soft clay should

![Figure 6. Horizontal load capacity of MRA in clay](image-url)
not be extrapolated to other soil conditions. For example, suction installation depth in sands is limited to about one diameter, which imposes a major limitation on load capacity that may be mobilized, a limitation that does not exist for the MRA.

In addition to weight efficiency, bulk can be even more significant when considering anchor handling and transport operations [4, 5]. Arrangement of the anchors depends on the details of the available anchor handling vessel (AHV) under consideration. However, if one considers a horizontally oriented suction caisson on the deck of an AHV, about 3 horizontally-oriented or four vertically oriented MRAs could occupy this same footprint. This efficiency can lead to fewer AHV trips and/or smaller AHVs.

4. Concluding Comments
This paper describes the potential advantages novel, integrated, and networked multiline ring anchor (MRA) system. Key considerations in anchor selection include cost, the potential for deep embedment when vertical load capacity is needed, and reliability. This paper compares the MRA to other existing anchors. Additionally, an example comparison is made between a conventional suction caisson anchor in soft clay. Basic conclusions are as follows:

1. The MRA is among a small group of anchors (3 others) a capability for achieving deep embedment in a variety of seabed soil conditions (Table 1), which is necessary for developing vertical load capacity.
2. The MRA is designed for multiline loading which, along with piles and caissons, provides a means for significantly reducing the number of foundation footprints, with associated cost reductions in materials, transport, installation, and geotechnical site characterization.
3. Installation costs for the MRA are medium (suction) to high (driving). This can put it at a disadvantage relative to low-cost installation methods such as drag embedment or dynamically installed anchors. However, drag embedment and dynamically installed anchors are not amenable to multiline loading, so the reduced number of anchors required by the MRA may tend to offset its greater installation cost.
4. The MRA capabilities for deep embedment and precise positioning during installation (Table 2) are favorable from the standpoint of reliability in that they ensure robust performance under unintended torsional loading and reliable predictions of load capacity.
5. The comparison of MRA performance to that of a suction caisson in soft clay indicate that (a) the MRA has a clear advantage in with respect to anchor efficiency under horizontal loading, and (b) a minor improvement over suction caissons under vertical loading. The relative performance of the MRA in regard to vertical load capacity can likely be improved by introducing keying flaps, which has been identified as a future research need.

Nomenclature

- $D$: diameter of the MRA or suction caisson
- $h$: tip embedment depth of the MRA, length of the suction caisson
- $k$: rate of strength increase per unit length
- $L$: length of the MRA
- $L_i$: load attachment depth of the MRA or suction caisson
- $L_{opt}$: optimum load attachment depth of the MRA or suction caisson
- $L_w$: length of the wing plates of the MRA
- $s_u$: undrained shear strength of soil
- $s_{um}$: undrained shear strength at mudline
- $t$: thickness of the ring anchor or suction caisson
- $t_w$: thickness of the wing plates
- $W_w$: width of the wing plates
- $z$: depth below mudline
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