

# **Optimal Design of a Deeply Embedded Ring Anchor in Soft Clay Overlying Bedrock under Vertical Loading**

**Junho Lee, Ph.D., A.M.ASCE<sup>1</sup>, Ragini Gogoi, S.M.ASCE<sup>2</sup>, Krishnaveni Balakrishnan, S.M.ASCE<sup>3</sup>, Charles P. Aubeny, Ph.D., P.E., F.ASCE<sup>4</sup>, Sanjay Arwade, Ph.D.<sup>5</sup>, Don DeGroot, Sc.D., P.E., M.ASCE<sup>6</sup>, Alejandro Martinez, Ph.D., A.M. ASCE<sup>7</sup>, and Ryan Beemer, Ph.D., A.M.ASCE<sup>8</sup>**

<sup>1</sup>Postdoctoral Research Associate, Zachry Department of Civil and Environmental Engineering, Texas A&M University, College Station, TX 77843; e-mail: [juno918@tamu.edu](mailto:juno918@tamu.edu)

<sup>2</sup>Ph.D. Student, Zachry Department of Civil and Environmental Engineering, Texas A&M University, College Station, TX 77843; e-mail: [raginigogoi@tamu.edu](mailto:raginigogoi@tamu.edu)

<sup>3</sup>Ph.D. Candidate, Civil and Environmental Engineering, University of Massachusetts Amherst, Amherst, MA 01003; e-mail: [kbalakrishna@umass.edu](mailto:kbalakrishna@umass.edu)

<sup>4</sup>Professor, Zachry Department of Civil and Environmental Engineering, Texas A&M University, College Station, TX 77843; e-mail: [caubeny@civil.tamu.edu](mailto:caubeny@civil.tamu.edu)

<sup>5</sup>Professor, Civil and Environmental Engineering, University of Massachusetts Amherst, Amherst, MA 01003; e-mail: [arwade@umass.edu](mailto:arwade@umass.edu)

<sup>6</sup>Professor, Civil and Environmental Engineering, University of Massachusetts Amherst, Amherst, MA 01003; e-mail: [degroot@umass.edu](mailto:degroot@umass.edu)

<sup>7</sup>Assistant Professor, Civil and Environmental Engineering, University of California, Davis, CA 95616; e-mail: [amart@ucdavis.edu](mailto:amart@ucdavis.edu)

<sup>8</sup>Assistant Professor, Civil and Environmental Engineering, University of Massachusetts Dartmouth, Dartmouth, MA 02747; e-mail: [rbeemer@umassd.edu](mailto:rbeemer@umassd.edu)

## **ABSTRACT**

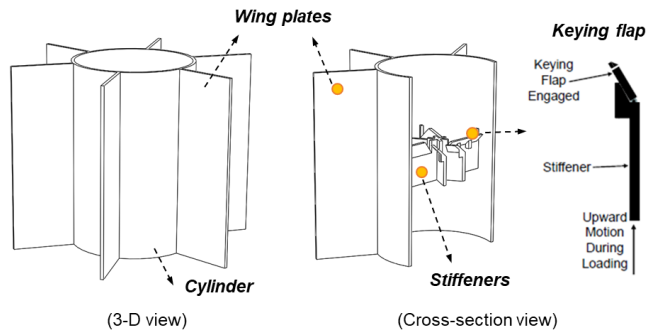
Offshore wind energy can play a significant role in addressing the clean energy policy goals of several countries, where floating offshore wind turbines (FOWT) can be preferred over the conventional fixed bottoms due to the water depth in the envisioned region. Since attractive sites for FOWTs will be located in extensive space in deep water, the potential sites are likely dominated by heterogeneous soils, such as clay to sand. This may require several anchor alternatives depending on soil type, resulting in increased costs and complexities of the single project. Therefore, the deeply embedded ring anchor (DERA) system has developed as a cost-effective solution for mooring FOWTs due to its attractive features: its installability in any soil type, its ability to be deeply embedded, availability to attach to various mooring systems, its multiline potential, and its compact size with high load capacity. In order to investigate the applicability of the DERA to various soil conditions in a specific site, this paper conducts a comparative example study and suggests the optimal design of the DERA in given site conditions. The findings from the study provide a platform to select a mooring system

considering geometric constraints and estimate the required physical features of the DERA for achieving the needed load capacity. The results show that the DERA is a feasible and cost-effective alternative for the heterogeneous seabed, shallow water depth, and thin sediment layer due to its attractive features.

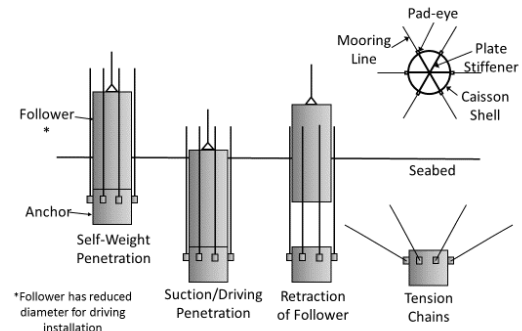
## INTRODUCTION

Offshore renewable resources in deep water far from the shore can have more attractive advantages due to more robust and consistent resources. This spurs the recent trend of the offshore wind industry to shift from the bottom-fixed wind turbines to FOWTs (Barter et al. 2020; Musial et al. 2016). However, foundation costs and risks associated with floating structures, resulting from increased anchor handling, logistic efforts, and complexity, increase as FOWTs are installed farther offshore and in deeper water (Harris and Grace 2015). The DERA has been devised as a cost-effective alternative for reducing costs and mitigating the risks. The DERA is a ring-shaped anchor designed to be deeply embedded in a wide range of seabed to secure multiple floating platforms (Aubeny et al. 2020, Figures 1 and 2). Attractive features of the DERA were validated by previous studies, including its ability to attach multiple mooring lines to a single anchor, its compact size, its installability in any soil, applicability to various loading conditions and fewer anchors, and its resilience under unintended loading conditions (Diaz et al. 2016; Lee and Aubeny 2020; Lee and Aubeny 2021; Lee et al. 2022).

Some key issues were identified from the parallel research currently in progress. First, the shared anchor concept is desirable where applicable, but it is not always feasible for all water depth conditions. This motivated the current study to estimate the DERA feasibility for all water depth and mooring systems. Second, the envisioned site for arraying FOWTs is likely to include heterogeneous soil conditions in addition to a shallow sediment layer overlying rock that suffers from penetrating the anchor into the seabed. For this reason, some stakeholders should prepare for several anchor solutions for a specific site, resulting in increased capital costs and complexity of the supply chain. In principle, DERA efficiency is maximized by deep embedment into the soil since higher load capacity is achievable with little added material cost. However, situations involving a shallow sediment mantle overlying rock can occur. The strategy is envisioned to achieve a high lateral/vertical capacity using wing plates or keying flaps (Figure 1). This requires additional material and fabrication costs, but it maintains compactness for efficient handling and transport. Moreover, there is no need for both penetrating the anchor into the rock and its post-installation grouting, resulting in installation cost and time savings compared to the conventional pile insertion into the bedrock. The feasibility of the features of the DERA is evaluated by comparison to existing anchor alternatives. Therefore, this research conducts a series of example comparative studies to address the key issues and emphasize the potential advantages of the DERA compared to other anchor alternatives.



**Figure 1. Six-wings DERA and strategies for enhancing load capacity (Lee et al. 2021)**



**Figure 2. The installation procedure of the DERA (Lee and Aubeny 2020)**

## KEY ISSUES FOR OPTIMAL DESIGN OF THE DERA

**Mooring system and applicability of multiline.** The suitability of the given anchor relies on the mooring types. Catenary systems typically work well in shallow water, but require a substantial mooring length in deeper water. Taut systems can have a shorter length than catenary systems, but their acceptability relies on several considerations, such as water depth and ocean usage. For these reasons, mooring system selection will be based on a determination of which system provides an optimal solution on a project-specific basis. Therefore, this study will evaluate the required mooring line length to select the proper mooring type considering geometric configurations such as water depth and turbine spacing. Anchor selection and optimizing its dimensions will then be conducted to understand further how the corresponding mooring type can be effective on anchor design.

One of the key features of the DERA, the shared anchor concept, is likely to be workable with many, but not all, taut and catenary mooring systems. In very shallow and very deep waters, the geometric constraints imposed by water depth and minimum turbine spacing may lead to excessively long mooring lines that offset the cost savings from fewer anchors in a shared mooring system. This spurs the current study optimizes the sweet spot ranges of the shared anchor depending on water depth, turbine spacing, and mooring types.

**Heterogeneous seabed and thin sediment layer.** Since attractive sites for FOWTs will be located in extensive space in shallow or deep water, the potential sites are likely dominated by heterogeneous soils, such as clay to sand (Figure 3). This may require several anchor alternatives depending on soil type, resulting in increased costs and complexities of the single project. However, the DERA mitigates these constraints and provides a cost-effective solution due to its attractive features: installability in any type of soil, the ability to be embedded in deep seabed, and its compact size with high load capacity.

The load capacity of a given anchor depends on soil profiles around the anchor. To be specific, penetrating the seabed to a certain depth is substantially important to developing the needed load capacity. Since the soil profile is typically stronger at deeper depth, embedding the DERA as

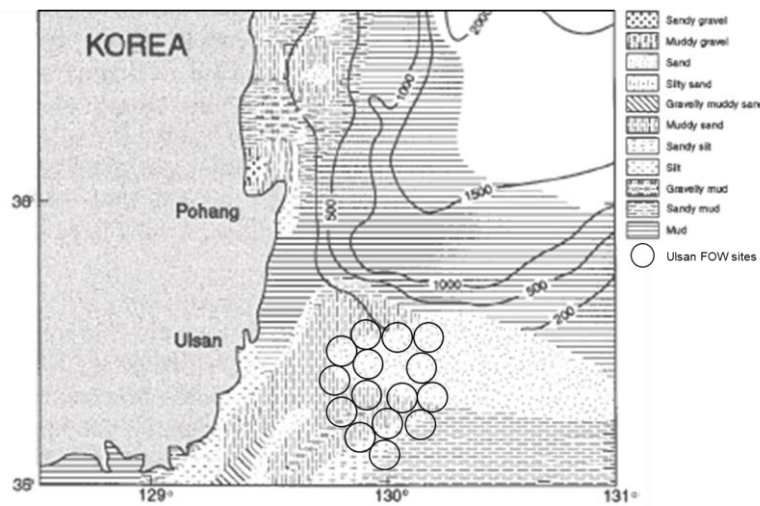
deeply as possible is a highly effective means of improving the load capacity. However, situations involving shallow sediment layer overlying rock can occur. As the sediment layer is thinner, the suitable anchor alternatives substantially diminish. In contrast to other anchor alternatives, the DERA can achieve a high load capacity with a compact anchor size in these situations.

## CONSIDERATIONS FOR THE COMPARATIVE STUDY

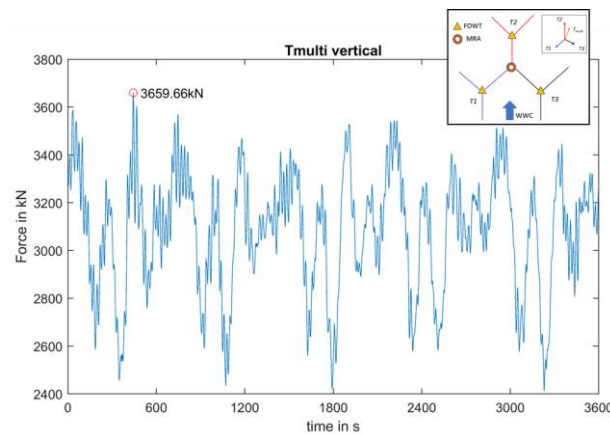
**Site conditions.** To estimate the key issues for the optimal design of the DERA, the current study selects the Ulsan floating offshore wind (FOW) site in South Korea for the following reasons: (1) water depths are relatively shallow (150-300 m), (2) the sediment layers are much thinner than other envisioned sites, and (3) soil profiles are heterogeneous in a single project. These conditions can be challenging to select or design proper anchors for the project. The Ulsan FOW sites are located about 60 to 70 km far from Ulsan city. The soil profiles of the sites vary from clay, gravelly clay, sandy clay, sandy silt, clayey sand, and sand (Figure 3). Although the Ulsan FOW site consists of various soil profiles, this study solely addresses clay conditions as one sizing exercise when optimizing anchor dimensions. Additionally, since detailed geotechnical investigations are currently ongoing, the thicknesses of the sediment layer in the clay region are assumed to be about 20 to 30 meters based on the previous study (Chough et al. (2000)). In the current study, the soil profile for the optimal design of the DERA is considered as typical normally consolidated clay: the undrained shear strength  $s_u = 5 + 2z$  with soil-pile adhesion  $\alpha = 0.7$  ( $s_u = 5$  kPa at the surface (Chough et al. 2000)).

**Extreme mooring loads for 15-MW FOWTs.** Lee et al. (2021) presented the extreme taut mooring line load calculated using National Renewable Energy Laboratory's (NREL) FAST v.8 analysis program. The computed ultimate resultant mooring load for the three-line shared anchor system considered NREL 15-MW reference turbines, OC4 semisubmersible platforms, survival load case (SLC), and 45 degrees taut mooring systems (Gartner et al. 2020; Viselli et al. 2015). Figure 4 represents the time-domain resultant force of the shared anchor system, which assumes the maximum tension force occurs when the wind wave current (WWC) direction is at zero degrees (Fontana et al. 2018). Since the uplift resistance is a major portion of the inclined loading from the taut mooring system, this paper focuses on the vertical component of the resultant force  $V_{multi}$  as a base case to optimize anchor design (Aubeny et al. 2003). To be precise, the anchor load demand is computed considering the factor of safety ( $F.S = 1.05$  for the SLC) based on the anchor guideline (ABS 2020). Thus, this paper assumes 3,843 kN ( $= V_{multi} \times F.S = 3,660 \text{ kN} \times 1.05$ ) as a vertical component of the required extreme mooring load for 15MW FOWTs. Preliminary findings from a study on the effects of water depth and single line mooring load demand currently in progress show this load demand value to be conservative in relation to shallow water depth and single line conditions.

**Assumptions for an example comparative study.** To optimize the anchor dimensions and mooring selection, the primary assumptions adopted in the study are as follows: (1) 900 MW floating offshore wind farm (two bottom circles shown in Figure 3) is considered to select appropriate mooring systems for the given sites, (2) 60 NREL 15-MW reference turbines (= 900 MW/15-MW FOWTs) are considered for assuming the same conditions in the comparative study, (3) three mooring lines are attached to the DERA as shown in Figure 6, (4) required anchor footprints and mooring line lengths for the shared anchor are calculated based on the previous study (Fontana et al. 2018), (5) in the case of the single mooring line, each FOWT has three anchors connecting to each mooring line, and (6) mooring line tension load is assumed as the same for all scenarios. Table 1 indicates each case of the required anchor footprints for the comparative study.



**Figure 3. Distribution of surface sediments on the Eastern margin of the Korean Peninsula and Ulsan FOW sites (Chough et al. 2000)**



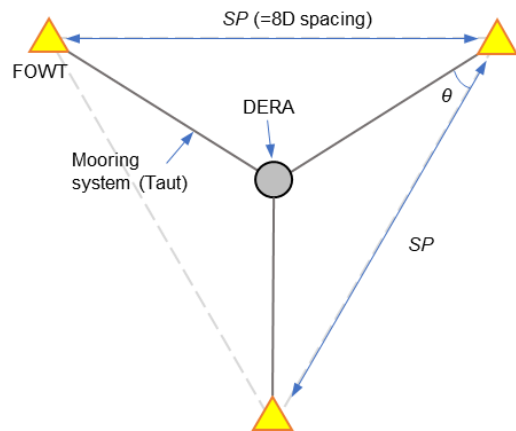
**Figure 4. Resultant vertical force of the DERA and its multiline configuration (Balakrishnan et al. 2020; Lee et al. 2021)**

## EXAMPLE COMPARATIVE STUDY

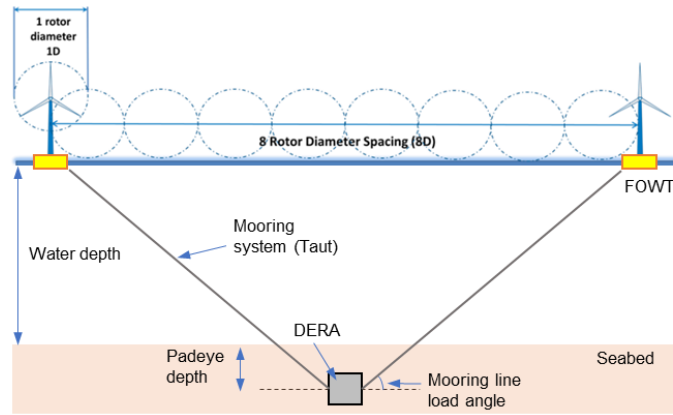
**Mooring system selection based on geometric constraints.** As noted earlier, considerations for selecting the mooring types include water depth, turbine spacing, and the multiline potential of the anchor. Since the shared anchor systems can drastically reduce the required anchor footprints, they offer substantial advantages, such as a reduction in the capital costs: anchor material, fabrication, and transport costs. Nevertheless, geometric constraints limit their range of feasibility. To better understand the feasibility range of the shared anchor system, the length of the mooring systems for the shared anchor system can be expressed as a function of geometric parameters, such as water depth and turbine spacing (Figures 5 and 6). The equation can be solely used for the case under taut mooring and the shared anchor systems.

$$ML = \frac{(WD + PD)}{\cos(\tan^{-1} SP / 2(WD + PD) \cos \theta)} \quad (1)$$

where  $ML$  is the length of the mooring line,  $WD$  is the water depth,  $PD$  is the distance from the seabed surface to the padeye depth,  $SP$  is the spacing between FOWTs, and  $\theta$  is the angle between the mooring line and the virtual spacing line. As this paper considers three wings DERA,  $\theta$  is assumed to be 30 degrees.



**Figure 5. Plan view of taut mooring system for the shared anchor concept**



**Figure 6. Elevation view of taut mooring system for the shared anchor concept (Courtesy of Musial 2018)**

In comparing the case of the catenary mooring system, the lengths of the catenary mooring system depending on the water depth are obtained by using the online based-commercial calculator (Mermaid-consultant 2022). As indicated in Table 1, attempting a shared anchor system in shallow water can lead to needlessly long mooring line lengths. By contrast, over about 500 m water depth, the shared anchor system can be feasible while considering reductions in capital costs and logistic efforts resulting from reduced vessel trips, which is proportional to the required anchor footprints. For this reason, the example study on the anchor selection and its optimal design for the Ulsan FOW assume the single-line TL system. The DERA can be feasible for all water depths since the anchor is used for a single line mooring system for shallow water

and simply revert to the shared anchor concept for deep water. Other considerations, such as environmental impacts, ocean uses, installation methods, and cost evaluations, have been identified as future research needs that should be addressed to select the mooring systems.

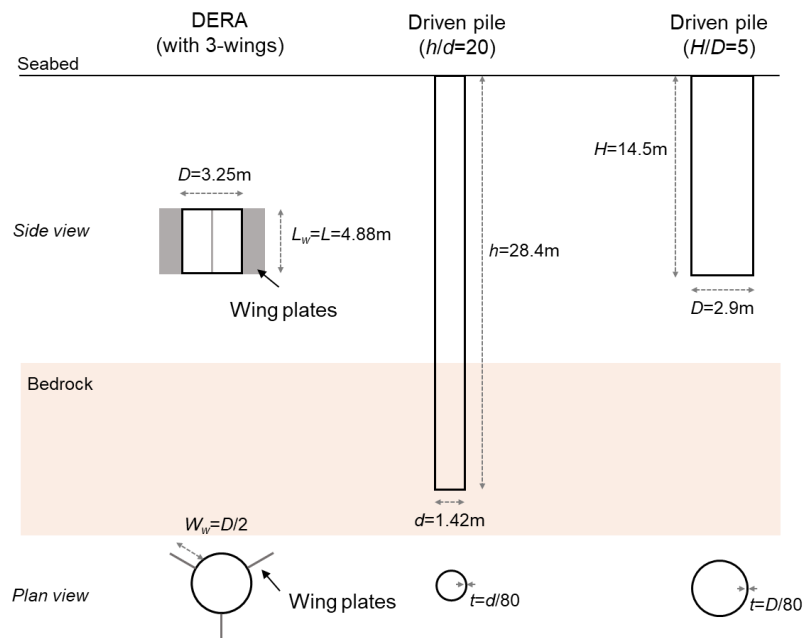
**Table 1. Required mooring line lengths**

| Scenarios         |                    | Shared anchor |                   | Single anchor |                   |                |                      |
|-------------------|--------------------|---------------|-------------------|---------------|-------------------|----------------|----------------------|
| Required anchors  |                    | 76 anchors    |                   | 180 anchors   |                   | 180 anchors    |                      |
| Mooring systems   |                    | Taut          |                   | Catenary      |                   | Tension Leg    |                      |
| Required moorings |                    | 180 moorings  |                   | 180 moorings  |                   | 180 moorings   |                      |
| Water depth (m)   | Mooring load angle | $ML_T$ (km)   | Total $ML_T$ (km) | $ML_C$ (km)   | Total $ML_C$ (km) | $ML_{TL}$ (km) | Total $ML_{TL}$ (km) |
| 100               | 5.8°               | 0.990         | 178.2             | 0.530         | 95.4              | 0.113          | 20.3                 |
| 150               | 8.3°               | 1.034         | 186.2             | 0.655         | 117.9             | 0.163          | 29.3                 |
| 200               | 10.9°              | 1.062         | 191.2             | 0.763         | 137.3             | 0.213          | 38.3                 |
| 300               | 15.7°              | 1.106         | 199.0             | 0.950         | 171.0             | 0.313          | 56.3                 |
| 500               | 24.8°              | 1.192         | 214.5             | 1.267         | 228.0             | 0.513          | 92.3                 |
| 1,000             | 42.4°              | 1.483         | 266.9             | 1.926         | 346.6             | 1.013          | 182.3                |
| 1,500             | 53.8°              | 1.860         | 334.8             | 2.513         | 452.3             | 1.513          | 272.3                |
| 2,000             | 61.2°              | 2.283         | 411.0             | 3.069         | 552.4             | 2.013          | 362.3                |

**Anchor types and dimensions.** Since the lateral load capacity of the anchor is relatively easy to achieve with shallow penetration into the seabed, most existing anchor alternatives, including drag-installed, gravity-based, suction caisson, and driven pile, work appropriately in a catenary system. However, the viable anchor solutions in taut and TL systems significantly reduce as the mooring line angle increases. For instance, certain anchors such as drag anchors in sands/stiff clay limit penetrating into the seabed to a depth enough for the required axial capacity. Also, load duration is critical for floating offshore wind projects since the anchor should resist long load duration, such as at least 25 to 30 years, under various loading conditions in addition to the sustained loading. Suction caisson can effectively withstand short-duration loads but suffer reductions in uplift resistance due to dissipating negative porewater pressure under sustained loading. Most existing anchor types are eliminated from the given conditions in this study: heterogeneous soils, long load duration, and TL system. Thus, the driven piles and the DERA are the remaining viable anchor alternatives.

Another critical constraint of the Ulsan FOW site is the thin sediment layer over the bedrock (about 20-30m). To estimate the anchor dimensions and required embedment depth in given soil profiles, semi-empirical approaches are utilized (Randolph and Murphy 2005; API 2000; Aubeny 2017; Anderson et al. 2005; Murff et al. 2005; Lee et al. 2022). Figure 7 indicates each anchor

case and its required dimension to meet the anchor load demand. Various strategies are envisioned to achieve high uplift resistance. The first is to enhance the axial capacity using wing plates or keying flaps (Figures 1 and 7). This requires additional material and fabrication costs, but this allows compactness for efficient transport. The advantages of attaching wing plates can be found in the works of Lee et al. (2022) and Lee et al. (2021). The second approach is to advance the driven pile into the rock using drilling and post-installation grouting methods. However, this requires additional installation time and efforts resulting in substantially increased costs and time. In comparison with the insertion of the pile into rock, suction or vibratory installation of the DERA is significantly more rapid and generates less noise. The DERA can take advantage of reducing installation costs and much fewer noise emissions during the anchor installation. The third approach is to increase the pile dimension to avoid insertion into rock. Although increasing the diameter of the pile can provide a huge cost saving in installation, its material and fabrication costs are still double compared to the 3-wing DERA. For example, since the material and fabrication costs are dependent on the total dry weight of steel ( $W_{dry}$ ), comparing  $W_{dry}$  can be instructive in the cost-saving effects of the DERA (O'Loughlin et al. 2015, Lee et al. 2020). Additionally, as the anchor sizes govern the required deck space on an anchor handling vessel (AHV), the compact size of the DERA allows to load more anchors onto the AHV: more promising for time and cost savings. For example, a limited and straightforward example study shows that one small AHV can load ten DERAs per trip in contrast to five piles per trip (assuming the deck space for the small AHV, width 12 m by length 40m).



**Figure 7. Optimal design of anchor alternatives and their strategies to achieve the required load capacity**

## CONCLUDING REMARKS

This study presents the potential advantage of the DERA for shallow sediment layer overlying bedrock and geometric constraints. To this end, the example comparative studies were conducted considering the specific site for the floating offshore wind farm. Key findings are as follows:

- The DERA provides a feasible alternative to the envisioned FOW sites that suffer relatively shallow sediment layers and geometric constraints such as turbine spacing and water depth.
- The DERA can be a more cost-effective alternative by virtue of its compact size, multiline potential, and availability to attach to various mooring systems.

## ACKNOWLEDGMENTS

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