Installability of a Multiline Ring Anchor System in a Seabed under Severe Environmental Conditions

Junho Lee
Zachry Dept. of Civil & Environmental Eng.
Texas A&M University
College Station, TX, USA
juno918@tamu.edu

Jinwuk Hong
Load and Response Research Department
Hyundai Heavy Industries
Seoul, South Korea
j.w.hong@hhi.co.kr

Charles P. Aubeny
Zachry Dept. of Civil & Environmental Eng.
Texas A&M University
College Station, TX, USA
caubeny@civil.tamu.edu

Sanjay Arwade
Dept. of Civil & Environmental.Eng.
University of Massachusetts Amherst
Amherst, MA, USA
arwade@umass.edu

Don Degroot
Dept. of Civil & Environmental.Eng.
University of Massachusetts Amherst
Amherst, MA, USA
degroot@umass.edu

Alejandro Martinez
Dept. of Civil & Environmental.Eng.
University of California Davis
Davis, CA, USA
amart@ucdavis.edu

Ryan Beemer
Dept. of Civil & Environmental.Eng.
University of Massachusetts Dartmouth
Dartmouth, MA, USA
rbeemer@umassd.edu

Krishnaveni Balakrishnan
Dept. of Civil & Environmental.Eng.
University of Massachusetts Amherst
Amherst, MA, USA
kbalakrishna@umass.edu

Yoonsoo Nam
Zachry Dept. of Civil & Environmental Eng.
Texas A&M University
College Station, TX, USA
ynam44@tamu.edu

***Abstract*—The trend of offshore wind energy in deeper water that is expected to shift from fixed to floating platforms requires a cost-effective anchor solution for floating offshore wind turbines (FOWTs). Multiline ring anchor (MRA) has been developed as a cost-effective solution for FOWTs due to its capability of anchoring multiple mooring lines, its high efficiency, and its availability to a wide range of soils and loading conditions. While previous preliminary studies on the anchor performance provide useful insights on how the potential advantages of the MRA can improve load capacity, these studies are limited to focusing on optimizing the anchor design in certain soil and loading conditions. By contrast, the MRA will be installed in seabeds under more complex conditions that depend on geological location, water depth of at-place, and environmental conditions, of which wind, current, and wave are major components. These may result in additional substantial extra capital costs, delays in the projects, and safety issues, when the complex conditions are not properly considered. Specifically, the installation time and expenses of the offshore anchor are very susceptible to anchor types, installation methods, and environmental conditions. For this reason, this paper compares two existing offshore anchor installation methods and different anchor types on the basis of their performance under the same severe environmental condition. In evaluating the installability of the MRA, this paper conducts a comparative scenario study. The results show that the anchor installations and anchor handling vessel (AHV) operations are sensitive to weather conditions and AHV sizes. In view of total weather standby, the results show that anchor types or installation methods have little effect on it due to their relatively shorter duration than other work sequences. However, the MRA can benefit in substantially reducing transport time and costs due to its compact size. The MRA can be more efficient and cost-effective than other alternatives under complex and severe weather conditions.**

Keywords—Anchor, Multiline, Floating, Wind, Renewable, Installation time, Morro Bay Call Area

I. Introduction

Attractive sites for offshore wind energy are located in deep water far from shore due to more robust and consistent resources as well as fewer aesthetic issues [1, 2]. This motivates a development by the offshore wind industry to shift from fixed to floating offshore wind turbines (FOWTs). However, the foundation costs for floating platforms increase with installing FOWTs in deeper and distant offshore locations [3]. The multiline ring anchor (MRA) has been developed to reduce these costs. The MRA is an open tube that can be deeply installed in seabed soils to secure multiple floating structures (Fig.1). Optional wing plates and keying flaps can be attached to the anchor for enhancing the load capacity of the MRA (Fig. 2).

Attractive features of the MRA consist of its multiline potential, its installability in almost any soil type, its compact size, its ability to reduce the number of required anchors, its applicability to various mooring systems, and its durability under unintended loading conditions [4, 5]. Lee et al. [6] emphasized that the MRA permits reducing the huge amount of capital costs for large-scale offshore wind energy projects due to its compactness, simplification of the anchor fabrication and installation process, and its ability to reduce the number of required anchors.

For achieving a cost-effective FOWT spacing in deeper waters, a taut mooring system is an attractive option [7, 8]. The recent trend of the scaled-up FOWTs and multiline configurations also require the MRA to endure extreme loading conditions. Additionally, previous studies on evaluating the workability of the installation work in deep water indicate the importance of understanding weather effects during anchor installations [9, 10]. The Bourbon Dolphin accident in 2007 was one example demonstrating the risks associated with anchor handling operation under severe weather conditions [11]. For these reasons, even though the MRA is intended to be suitable for a wide range of soil and various loading conditions, this study addresses the installability of the MRA in clay under severe weather conditions, with a specific focus on anchor dimensions for vertical load demand. Therefore, this research conducts a comparative scenario study using an in-house probability analysis code to understand the installability of the MRA depending on weather conditions, installation methods, and AHV sizes.

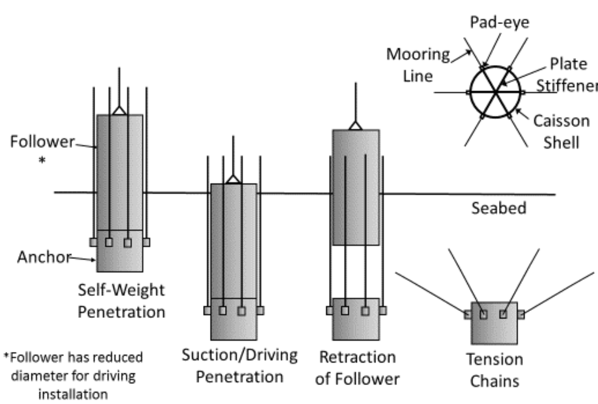

Fig. 1. The installation procedure of the MRA [5]

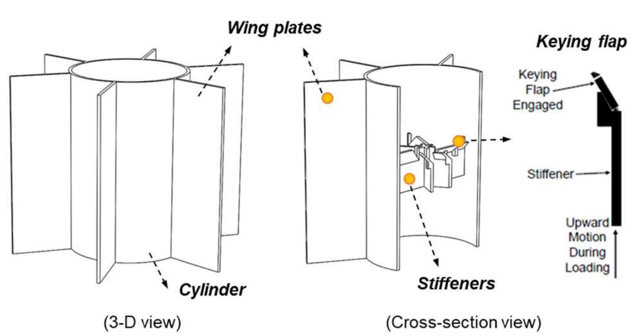

Fig. 2. Six-wings MRA and load capacity enhancement strategies

II. Scenarios for Installbility Analyses

A. Site Conditions

In contrast to the East Coast of the United States, a significant portion of potential offshore wind resources on the West Coast exists in deep and distant water [12]. This leads to a need for cost-effective anchor systems in order to secure FOWTs. Additionally, the Bureau of Ocean Energy Management (BOEM) identified the Call Areas as potentially suitable for offshore wind farm leasing on the West Coast, including the Morro Bay Call Area, Diablo Canyon Call Area, and Humboldt Call Area [12]. To understand the installability of the MRA, the current study selects the Morro Bay Call Area for the following reasons: (1) buoy data such as time-varying wind speed and significant wave height are available, and (2) the soil profiles, excepting those with exposed bedrock, are suitable for MRA deployment. Although BOEM recently added the Morro Bay Extension Call Area, this study focuses on the original Call Area presented in 2018 (Fig.3), since more data were readily accessible from this area [12].

The Morro Bay Call Area is likely dominated by clay [13, 14]. In the current study, the assumed soil profile for selecting anchor dimensions is a typical normally consolidated clay (undrained shear strength s_u=5+2z with soil-pile adhesion α=0.7) [15]. This study also utilizes the twenty years of weather data to evaluate the installability of the MRA under severe environmental conditions. TABLE I summarizes the locational data for that Call Area.

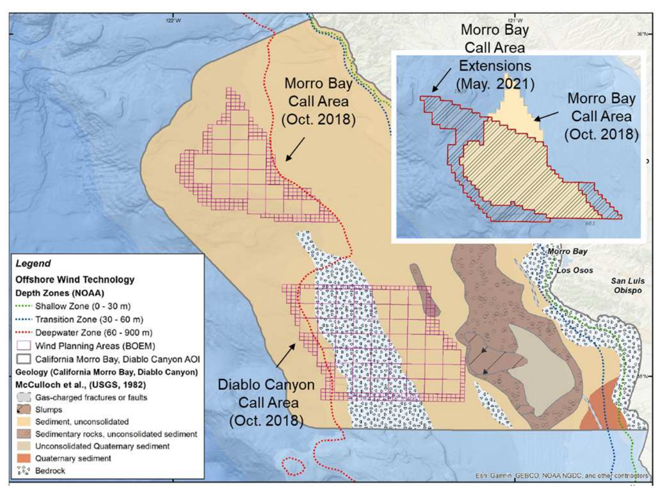

Fig. 3. Geology map for California Morro Bay Call Area [14]

TABLE I. Locational Data for Morro Bay Call Area [12]

Item		Data	Item	Data
Capacity potential		2,419 MW	20-year meand wind speed (W_s) at 150m	9.8 m/s
Size		806 km^2	Significant wave height (H_s)	2.47 m
Area centroid	Latitude	35.6N	Mean water depth	1,013 m
	Longitude	121.8W	Distance from site to port	317.7 km

B. Extreme Mooring Loads for 15-MW FOWTs

Lee et al. [8] presented that the multiline potential, the use of the taut mooring systems for the scaled-up FOWTs, and severe weather conditions may impose a more extreme loading condition on the anchors overall. Thus, it is essential to estimate the extreme multiline mooring loads of the 15-MW FOWT under severe weather conditions. The extreme taut mooring line load was computed by using National Renewable Energy Laboratory's (NREL) FAST v.8 analysis program. NREL 15-MW reference turbines, OC4 semisubmersible platforms, survival load case (SLC), and 45 degrees taut mooring systems are considered to estimate the ultimate resultant mooring load (TABLE II and Fig. 4) [16-18]. The multiline configuration of the floating structures can be illustrated through the following simple steps. First, the offshore floating platforms with three single lines are linked to each anchor, and second, the anchors are shared between lines (Fig. 4). As the preliminary study indicated that the maximum tension force occurs when the wind wave current (WWC) direction is at zero degrees, the current study assumed WWC=0° [19]. To determine the time-domain multiline resultant force of the anchor, the anchor forces from three lines were superimposed. Since the vertical load capacity is a major portion of the inclined loading from the taut mooring systems, estimating the axial load capacity is essential to understand the anchor performance under inclined loading [20]. Thus, the vertical component of the computed resultant force V_{multi} is considered as a base case to optimize the anchor dimensions. To be precise, the required anchor load capacity is calculated considering the factor of safety ($F.S$=1.05 for the SLC) from the anchor capacity guideline [21]. Therefore, this study assumes 3,843 kN (= $V_{multi} \times F.S$ = 3,660 × 1.05) as the axial component of the ultimate multiline load demand for 15-MW FOWTs.

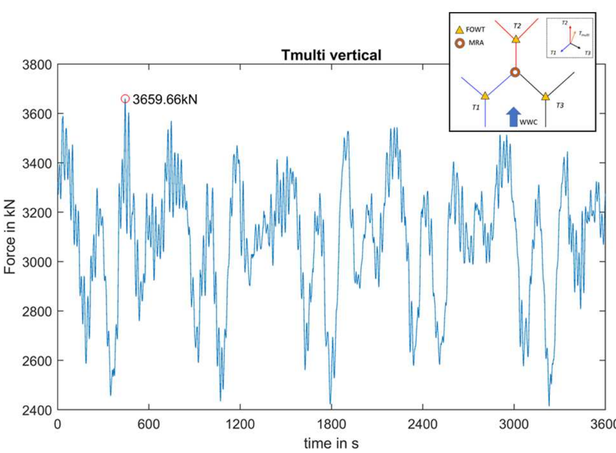

Fig. 4. Resultant vertical force of the MRA and its multiline configuration (upper right) [16]

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TABLE II. PROPERTIES OF FOWT AND ENVIRONMENTAL CONDITIONS FOR MOORING DESIGN UNDER EXTREME CONDITIONS

NREL 15-MW FOWT [17]		Survival Load Case [18]	
Rotor diameter	240 m	Conditions	Survival non-operating
Hub height	150 m	W_s at hub height (500-yr)	45 m/s
Rated speed	10.6 m/s	H_s (500-yr)	12 m
Platform	NREL OC4 Semisub.	Peak spectral wave	15.3 s
Water depth/ radial distance	1,000 m/ 1,808 m	Current speed	0.55 m/s

C. Anchor Types and Dimensions

Previous studies [4] presented the potential advantages and constraints of existing anchor solutions for floating platforms. According to their studies, MRA, suction caisson, dynamically installed pile, drag anchors, SEPLA, and DEPLA are acceptable for securing floating structures in deep water depths of greater than 60m. However, since FOWTs are placed in arrays, one of the necessary features is multiline potential. For this reason, Lee and Aubeny [5] screened the anchor alternatives based on multiline potential in addition to geotechnical efficiency. After screening, the remaining anchors are MRA and suction caisson. Thus, this study focuses on three anchor alternatives: suction caisson (SC), small diameter MRA with three wings, and large diameter MRA without wings. The base case is a suction caisson having an aspect ratio H/D=5 and vertical load capacity to resist the multiline anchor load demand for 15-MW FOWTs. The two MRAs are dimensioned to satisfy the same load demand as suction caisson. As noted earlier, a typical normally consolidated clay profile is selected as a base case analysis for determining anchor dimensions (s_u=5+2z) [15]. All anchor alternatives are installed to the same tip depth and have the same uplift resistance (Fig. 5). Semi-empirical approaches are used to estimate the anchor dimensions. [8, 22, 23] TABLE III and Fig. 5 indicate each anchor case and its required dimension to meet the required anchor load capacity.

D. Scenarios based on Installation Methods and AHV sizes

In evaluating the installability of the MRA, comparison to conventional suction caissons can be informative. As a basis for comparison, the current study considers suction for installing the MRA. Additionally, a comparison to the other installation method, such as hammer driving, is also conducted to evaluate the proper installation method for the MRA. While the possible installation methods for the MRA can vary from suction installation, hammer driving, and vibratory hammering, suction and hammer-driven installation are most suitable to this site. As noted earlier, the MRA requires extracting the followers after anchor installation (Fig. 1), and the extraction time should be considered as part of the anchor installation process. Specific details for extracting the followers from the anchors have been identified as a future research topic, so they will not be included in this study.

Since the operating for anchor handling vessels (AHVs) during anchor installation are sensitive to the weather conditions and their sizes, scenarios for the installability analyses vary based on the dimensions of the AHVs: from large to small sizes (e.g., small-size = length l × width w =107 m × 25 m, mid-size = l 75 m × w 17 m, and small-size = l 40 m × w 12 m [24, 25]). Thus, the current study conducts twelve base scenario studies to understand the installability of the anchors depending on installation methods and the dimensions of the AHVs, as indicated in TABLE III.

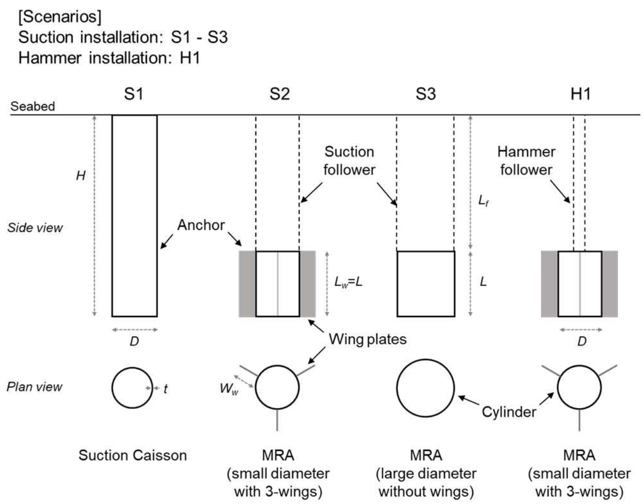

Fig. 5. Anchor installation scenarios

TABLE III. ANCHOR DIMENSIONS AND SCENARIOS

Base Scenarios		**S1**	**S2**	**S3**	**H1**
Installation methods		Suction	Suction & extract	Suction & extract	Hammer driving
Anchor type		SC	MRA (3-wings)	MRA (no wing)	MRA (3-wings)
Anchor dimensions		D=2.9 m, H=14.5 m, t=D/70	D=3.2 m, L=4.8 m, t=D/70	D=4.2 m, L=4.8 m, t=D/70	D=3.2 m, L=4.8 m, t=D/70
Capacity enhancement		-	3-wings: W_w=D/2, L_w=L	-	3-wings: W_w=D/2, L_w=L
Follower dimensions		-	D=3.2 m, L=9.7 m	D=4.2 m, L=9.7 m	D=0.8 m, L=9.7 m
AHV sizes	Small	**S1-1**	**S2-1**	**S3-1**	**H1-1**
	Mid	**S1-2**	**S2-2**	**S3-2**	**H1-2**
	Large	**S1-3**	**S2-3**	**S3-3**	**H1-3**

III. COMPARATIVE SCENARIO STUDY

In evaluating the installability of the MRA, this paper conducts a comparative scenario study. The procedure adopted in the study is to (1) gather twenty years of weather data at Morro Bay Call Area, (2) define work sequences and weather limitations, (3) evaluate the installation and extraction time for each case, and (4) estimate the workability of work sequences using the in-house probability analysis code. The details will be discussed in the following sections.

A. Scheduling Management System

Hyundai Heavy Industry (HHI) has developed the scheduling management system, an in-house probability analysis code, to evaluate the workability of the offshore installation projects based on weather data at a specific installation site [9]. Through the system, unexpected risks such as a time delay or fatal accidents caused by the weather conditions can be mitigated by increasing the efficiency of the offshore works or reducing the complexity of the works and the gap between a plan and the actual operations. The following data and definitions are required for the workability simulations: installation site, measured weather data of the site, the definition of the work sequences, the definition of weather limitation for each work sequence, the definition of working duration for each work sequence, and target start day. The results of the analyses are suggested with a percentile weather standby. Reliable and appropriate scheduling management of the installation works can be obtained by the computed results. As mentioned above, Morro Bay Call Area is selected as an installation site to understand the installability for the MRA. Other input data will be discussed in the following section. Fig. 6 indicates the workflow of the scheduling management system.

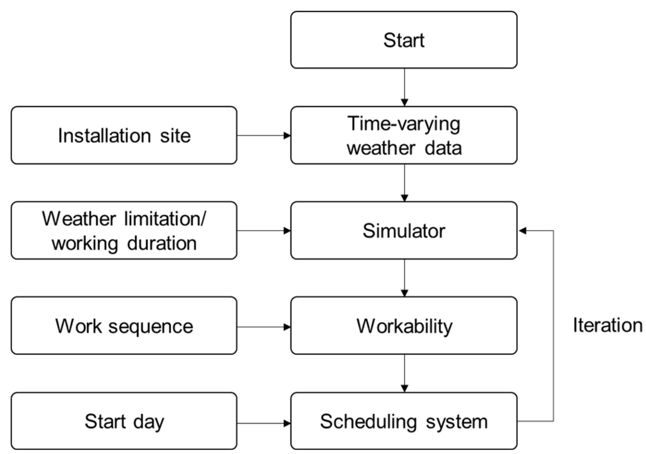

Fig. 6. Workflow of scheduling management system [9]

B. Inputs for the Analyses

1) Twenty-years Buoy Data: In evaluating the workability of the MRA under severe weather conditions, 20-years of buoy data were used as base environmental conditions. While the buoy data includes significant wave height, wind speed, wind direction, atmospheric pressure, and temperature, this study focuses on two primary parameters affecting the AHV operations: significant wave height H_s and wind speed W_s. For reliable weather conditions close to Morro Bay Call Area, the current study collected time-varying H_s and W_s of Station 46028 (location: 35.8N and 121.9W) from the National Oceanic and Atmospheric Administration's (NOAA) National Data Buoy Center [26].

2) Work Sequences and Weather Limitations: Typical anchor installation sequences are assumed as indicated in TABLE IV. Anchor installation and follower extraction vary depending on anchor types and installation methods. Except for these two work sequences, the rest are assumed to be the same for all scenarios. The work duration is defined as the time window that is below the weather limitation without any interruption. To estimate the work durations acceptably, the primary assumptions are as follows: (1) three AHV having cranes for anchor handling manages the whole sequence for assuming the same conditions in all scenarios, (2) each AHV conducts each mooring work sequence respectively and simultaneously, (3) the time for lowering anchors and additional deck handling is assumed as 30 minutes per 100 m deeper water depth, (4) anchor installation time includes extra time due to self-weight penetration and deck handling of the anchors in addition to the exact installation time, (5) Extraction time of the followers was assumed as similar to the installation time, and (6) weather limitation depends on AHV sizes, as indicated in TABLE V. The basis for the above assumptions can be found in the previous studies and personal communications regarding AHV handlings and anchor installations [27, 28].

TABLE IV. EXAMPLE OF WORK SEQUENCES FOR ANCHOR INSTALLATION: S2-2 CASE

Work Sequences	Duration (hours)	Weather Limitation	
		H_s (m)	W_s (m/s)
Anchor lowering & deck handling	6	2	10
MRA installation (suction)	6[a]	2	10
Follower extraction (suction)	6[b]	2	10
Simultaneous three mooring laying (using 3 AHVs)	24	2	10
Simultaneous three mooring hook up (using 3 AHVs)	9	2	10
Tensioning and survey (using 3 AHVs)	18	1.5	10
Total duration	69	-	-

[a] Installation duration varies depending on anchor types and installation method (TABLE VI)
[b] Follower extraction duration varies depending on anchor types and installation method (TABLE VI)

TABLE V. WEATHER LIMITATION BASED ON AHV SIZES

AHV Sizes	Duration (hours)	Weather Limitation	
		H_s (m)	W_s (m/s)
Small	General work sequences	1.5	7.5
	Tensioning and survey	1.25	7.5
Mid-sized	General work sequences	2	10
	Tensioning and survey	1.5	10
Large	General work sequences	2.5	12
	Tensioning and survey	2	12

3) Suction Installation and Extraction: Since seepage inflow during suction installation in clay can be negligible, the penetration rate is estimated by a simple flow rate calculation. Given practical applications, this study assumes that a standard pump can have a capacity of approximately 110 m^3/hour. The pumping installation time was established by the following simple definition: T_{ins} = Inner volume of the anchor/pump capacity = Vol_{in}/Q_{pump}. In addition to pumping time, this paper considers installation time to include the time required for self-weight penetration and deck handling of the anchor. Thus, the suggested installation time for scenarios S1 to S3 are 6, 6, and 8 hours, respectively. To match the three-hour interval of the weather data, the estimated installation times were adjusted to be even multiples of the weather increments in the simulations. For instance, the input for the analyses was finally changed to 6, 6, and 9 hours (TABLE VI). The extraction times of the followers were treated in the same manner. The extraction time of the followers includes exact extraction time by the simple flow rate calculation and extra time due to deck handling and pulling anchor. For this reason, the current study assumes that the extract time is similar to the installation time. Another main consideration for suction installation in clay is underpressure. Applying sufficient underpressure is required to overcome soil resistance. Additionally, as excessive underpressure can induce instability during installation, the study entails a second calculation of the maximum allowable underpressure. Fig. 7 shows the calculated minimum required underpressure u_{req}, maximum allowable underpressure u_{cr}, and self-weight penetration depth. As an example, due to the resistance from the wing plates, the MRA installation requires more underpressure than the suction caisson, and the self-weight penetration depth for the MRA is shorter than that of the suction caisson. The current study also identified that typical pump specifications for the suction installation could manage the computed underpressures for all scenarios regarding suction installation.

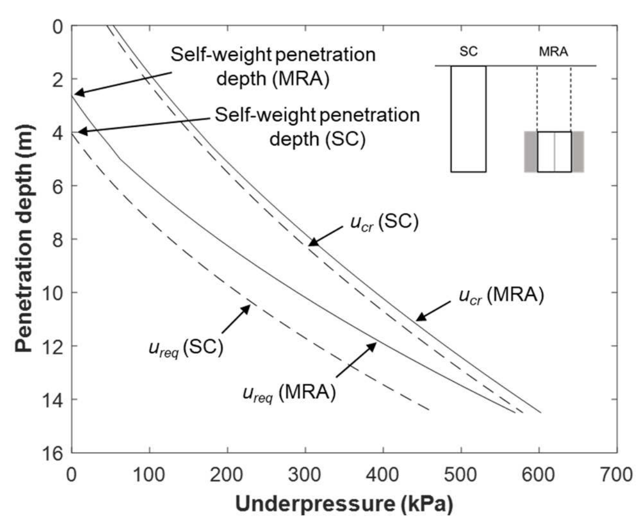

Fig. 7. Suction installations of the MRA and suction caisson in clay

4) Hammer Driving and Extraction: For offshore pile installation in deep water, underwater hydraulic impact hammers, clamped to the pile head or with a follower, can be utilized. Since impact hammers generate a force pulse that causes the pile to move downward, wave equation analysis determines the pile driving [29, 30]. The wave equation analysis is based on computer programs due to the complexity of the soil resistance mechanism. This paper adopts the calculated values from the program that has been validated through extensive cases and assumed using typical hammer size. For scenario H1, the necessary resistance to driving is about 4,350 kN, including the follower resistance. Thus, based on engineering experiences, the rate of penetration for the computed driving resistance can be considered 35-40 blows per 0.3 m, and it is applied to determine the installation time by hammer driving [31]. The proposed follower for the hammer driving has a smaller diameter than the anchor due to the following possible extraction strategies. First, the smaller follower permits easier extraction after installation. This allows the use of conventional equipment, such as a winch or vibratory hammer, to extract the follower without excessive soil resistance. Second, the smaller follower permits the possibility of leaving a sacrificial follower in-place after installation. Since the compact size of the follower does not require a lot of material and fabrication costs, the sacrificial follower can be a cost-effective solution when unexpected conditions occur that can induce delays or additional cost, e.g., jamming of the follower in strong soil or severe weather conditions. The required extraction force is estimated at 310 kN (=31.6 tons) considering the follower weight and reduced adhesion factor α=0.3 caused by soil disturbance right after the installation. As the typical load capacity of the winch on vessels is up to 500 tons with the rate of 5 to 20 m/min, extraction of a follower about 10 m in length requires just a few minutes [32], which is considered negligible. Therefore, for the analyses, the current study assumes three hours as an anchor installation time that includes extra time due to self-weight penetration and deck handling of the anchor (TABLE VI).

TABLE VI. SUGGESTED INPUT DATA FOR ANCHOR INSTALLATION AND FOLLOWER EXTRACTION

Scenarios	Suction			Hammer
	S1	***S2***	***S3***	***H1***
Anchor types	SC	MRA (3 wings)	MRA (no wing)	MRA (3 wings)
Anchor installation time	6 hours	6 hours	9 hours	3 hours
Follower extraction time	-	6 hours	9 hours	-

IV. RESULTS

In order to understand the effects of anchor types, their installation methods, AHV sizes, and the weather conditions, this study conducts probability-based comparative scenario studies. TABLE VII provides an overview of each comparative study. Additionally, the term “monthly mean weather standby” refers to the mean value of the waiting time per month, which is based on a probabilistic analysis of the weather data. To be precise, the waiting time of each probability per month, indicated in TABLE VIII, is obtained by the scheduling management system. The mean of the computed values is then defined as a monthly mean weather standby (TABLE IX). Thus, the workers can utilize the weather standby of every percentile to optimize the installation and mitigate problems caused by weather conditions. For example, July or August might be a more opportune time for the installation works than December or January (TABLE IX). For these reasons, the monthly mean weather standby can be a good measure to understand the installability of the anchors under severe weather conditions.

TABLE VII. OVERVIEW OF COMPARATIVE STUDIES

Parameters	Comparative studies	
	Description	***Scenarios***
Anchor types	SC vs. MRA(3-wings) vs. MRA(no wing)	S1 vs. S2 vs. S3 for each AHV size (i.e., S1-1 vs. S2-1 vs. S3-1)
Installation methods	Suction vs. Hammer driving	S2 vs. H1 for each AHV size (i.e., S2-1 vs. H2-1)
AHV sizes	Large vs. Medium vs. Small	AHV sizes for each base scenario (i.e., H1-1 vs. H1-2 vs. H1-3)

A. *Effects of Anchor Types and Installation methods*

The current study considers three types of multiline anchors to secure FOWTs: suction caisson, small diameter MRA with three wings, and large diameter MRA without wings. The dimensions of each alternative vary to achieve parity in axial capacity for anchoring the FOWTs under the same conditions. In view of the input data for the analyses, the differences in the three anchors are reflected in the installation work sequences and their duration. Additionally, the analyses for the MRA required additional time for follower extraction. This implies additional weather standby for the works and may affect the extra cost in terms of the installation costs compared to the suction caisson. However, the analyses show that the differences in the weather standby between both cases are unnoticeable, except for the S3-1 case (MRA without wing plates and operated by small AHVs). As shown in Fig. 8, in May and November, the MRA without wings handled by small AHVs is expected to require more than 15% of weather standby of the suction caisson or the MRA with 3-wings. The difference between predicted weather standby for other cases, such as mid-sized and large AHVs scenarios, is generally within 3% and always within 12%. A possible explanation of this trend might be related to the relatively short duration of installation and extraction relative to the duration of the entire work sequence.

In the case of installation methods, likewise anchor types, the difference in installation methods is also represented as the duration in terms of the input parameter. For this reason, the series of the S2 and H1 cases were selected to understand the effects of installation methods (i.e., suction vs. hammering). The results show that both cases have a similar trend, but the gap between the two ways increases as AHV sizes decrease. The difference between suction and hammer driving is generally within 5% and always within 14%.

B. Effects of AHV Sizes

Unlike the cases of the anchor types and their installation methods, the impacts of AHV sizes on the weather standby are more apparent. As the AHV size increases, illustrated in Fig. 8, the monthly mean weather standby decreases up to about 90%. The most pronounced decreases in standby time with increasing AHV size occur between September and November. Since the weather limitations of the AHV depend on its size, the sensitivity of the weather increases with decreasing AHV sizes. Considering the computed results, the most efficient season for anchor installation is the summer due to the shorter weather standby times. As an example, the mean weather standby of the summer has shown about 25% of that of the winter. Additionally, even though bigger AHV can reduce waiting time for the anchor installations, the cost-effectiveness should be considered with other aspects related to logistics and transport like a vessel day rate, AHV specifications, crane capacity for lifting anchors, etc.

TABLE VIII. WAITING TIME OF EACH PROBABILITY PER MONTH: S2-2

Percentile	**Waiting time of each probability per month (hours)**					
	Month					
	Jan.	***Mar.***	***May***	***Jul.***	***Sep.***	***Nov.***
10%	84	48	33	0	3	39
20%	189	117	87	21	36	105
30%	294	210	138	48	69	165
40%	420	294	189	75	105	228
50%	528	456	240	105	144	291
60%	615	582	303	141	192	369
70%	717	726	384	198	261	495
80%	903	879	495	264	357	654
90%	1233	1071	627	381	498	978
100%	2295	1560	1287	945	1743	1806
Mean	607	508	296	157	243	410

TABLE IX. MONTHLY MEAN WEATHER STANDBY: MEDIUM AHVS OPERATION CASES

Month	**Monthly Mean Weather Standby (hours)**			
	Scenarios			
	S1-2	***S2-2***	***S3-2***	***H1-2***
Jan.	597	607	626	580
Feb.	516	523	587	509
Mar.	486	508	515	479
Apr.	384	390	392	382
May	291	296	300	284
Jun.	317	325	332	313
Jul.	154	157	159	154
Aug.	113	123	129	111
Sep.	237	243	249	236
Oct.	295	306	313	288
Nov.	380	410	423	361
Dec.	534	567	618	517

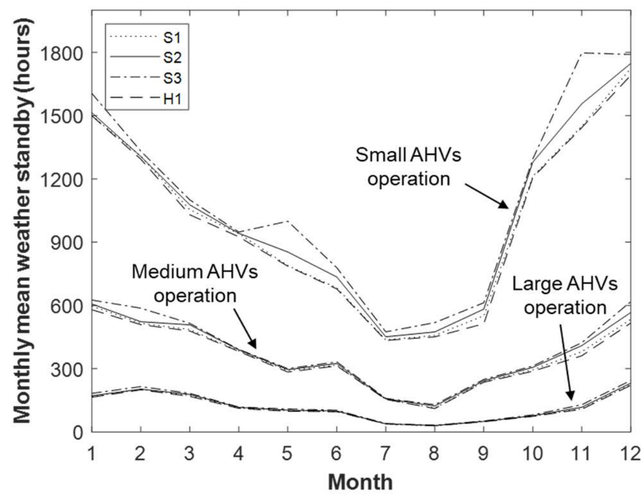

Fig. 8. Monthly weather standby for each scenario

C. Discussions

Since the study focuses on estimating weather standby caused by anchor types, their installation, and operating AHV sizes, other aspects, such as environmental policy, cost-effectiveness, and embedment depth, should be considered for realistic applications. For example, in comparing the cases S2 and H1, suction installation imposes limits on the anchor aspect ratio and therefore installation depth (e.g., H/D = 6 to 7). On the other hand, no strict depth limits apply to hammer-driven installation. However, impact-hammer installation may cause environmental issues like noise and vibrations, mitigation of which may be required for environmental-friendly offshore operations. A vibratory hammer can be an attractive alternative to installing the MRA, which is currently a focus of ongoing parallel research.

In view of solely installation and extraction time, suction caisson seems more cost-effective than the MRA due to the shorter required duration. However, Considering the whole work sequences and their total duration, the results show that anchor types or installation methods have little effect on total weather standby due to their relatively shorter duration than other work sequences. e.g., work duration by installation methods = 3 to 8 hours, and the required hours for one chain laying = 24 hours (TABLE IV and Fig. 8). The MRA can be a cost-effective means than suction caisson regardless of installation methods. It can benefit in substantially reducing transport, material, and fabrication costs due to its compact size [6]. Since the sizes of the anchors govern the required deck space on an AHV, a smaller anchor can be fit onto the vessel to load more anchors, resulting in time and cost savings (e.g., load per trip for mid-sized AHV: five suction caissons vs. ten MRAs, Fig. 9). Considering the distance site to port and AHV day rate, the time and cost-saving effects of smaller anchors are more attractive and promising. A limited and straightforward example study indicated in TABLE X provides that the compactness of the MRA can save substantial transport time and costs.

Since FOWTs in deep water require taut mooring systems, the anchors for securing floating structures should have reliable vertical capacity under sustained loading. A significant portion of the uplift resistance of the suction caisson is from the reverse end bearing, which results from transient negative excess porewater pressures at the caisson tip. Under sustained loading, these transient excess porewater pressure cannot be relied upon to provide resistance to uplift, thereby reducing the available vertical load capacity of the anchor. By contrast, the MRA achieves its vertical load capacity by largely through adhesion and end bearing on the various components of the anchor, including the core tube, stiffeners, and wing plates [8, 33]. Resistance to uplift from these sources does not rely on transient negative porewater pressures; therefore, significant loss in uplift capacity is not expected under sustained loading from taut mooring systems.

TABLE X. LIMITED EXAMPLE STUDY FOR TRANSPORT COSTS

Anchor types	**AHV size**	**Required anchors**	**Load per trip**	**Total trips**	**One-trip duration (round)**	**Transport cost per one AHV[c]**
Suction caisson	Mid-sized	160 anchors[a]	5	32	29 hours[b]	24.7$M
MRA (3-wings)			10	16		12.4$M

[a] capacity potential at the site/15-MW FOWTs = 2400/15 =160
[b] assumes trip time per one AHV and the typical speed of 22 km/h: 318 km/22 km/h*2=29 hours
c assumes unit day rate of a vessel (=$20,000) and an operational weather window of 75% for one AHV: Transport cost= total trip * duration * unit day rate of a vessel * (1/operational weather window) [24, 25, 27]

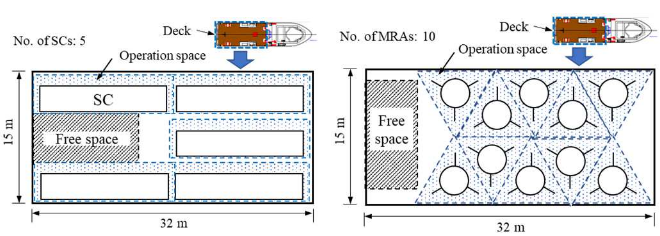

Fig. 9. Examples of loading diagram for mid-sized AHV: Suction caissons (left) and the MRAs (right)

V. CONCLUDING REMARKS

This study presents the potential installation methods of the MRA and its installability under severe weather conditions. To this end, the comparative scenario studies were conducted by using probability analyses with time-varying weather data at the site. Key findings are as follows:

- The probability-based Monthly mean weather standby can be a good measure to understand the installability of the anchor under severe weather conditions.
- The MRA with 3-wings requires up to 10% more installation time for the Morro Bay Call Area than suction caisson due to the added time required for extraction of the follower. However, the difference in installation times between a conventional suction caisson and an MRA is more generally within 3%, which is considered negligible.
- The sensitivity of the weather for anchor installation increases with decreasing AHV sizes. The computed results show that the summer can be a more efficient season to install anchors than winter due to shorter weather standby (about 25% of winter weather standby).
- The MRA can be a more cost-effective alternative by virtue of its compact size resulting in significant reductions in transport time and costs.

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