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Testing of drag embedment anchors under uplift and out of plane loading in sand

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ABSTRACT: While the effects of uplift loading and out of plane loading on drag embedment anchors (DEA) are well documented for soft clay soil conditions, their behaviour in sand is less understood. Our research contributes to an improved understanding of the use of DEAs for floating renewable energy in sand seabeds in shallow water, which can sustain these inclined loads. An experimental programme has been initiated to investigate the impact of inclined loads on two different DEA scale models, which are commonly utilised in offshore applications, in a sand test bed. The DEAs have been subjected to uplift (5 °, 10 °, 15 ° and 20 °) and side (15 °, 30 °, 45 ° and 60 °) loads at installation loads varying from 50 % to 100 % of the ultimate holding capacity (UHC) in the test bed. Our results show that DEAs can withstand substantial loads even when their capacity decreases as a result of an increase in uplift loading. Similar results are observed when the DEA is loaded out of plane. The study shows that resistance to inclined loads can be increased by raising the DEA installation load in relation to the UHC. Raising the level of confidence in DEA for usage in scenarios including sand seabed and shallow water is vital, as floating offshore wind contributes significantly to reaching net zero.

Keywords: drag embedment anchor; uplift; out of plane loading; sand

1 BACKGROUND

Recent developments in anchoring systems for floating energy devices has highlighted the requirements for more detailed studies in the uplift and out of plane loading resistance of DEAs, and more specifically in non-cohesive seabeds. Planned projects indicate requirements for anchor points that can take uplift and out of plane loading, with a significant portion of these projects having sand seabed conditions.

In general practice with DEAs, the mooring line will be horizontal on the seabed before it enters the soil and connects to the anchor shackle. Due to design optimization of the mooring system, it may be preferable to have mooring system with a small uplift angle, to keep mooring line components off the seabed, or a semi-taut mooring. The effect of uplift has been studied in soft clay soil conditions (Aubeny, 2011), (Fulton, 1994), (Randolph, 2017), (Vryhof, 2015) and incorporated into some codes (API, 2003), (DNV, 2012) but little work has been done in non-cohesive soils (Puech, 1984). The work done in non-cohesive soils presents the results of model tests and shows a reduction in DEA capacity with increasing uplift. The effect of the DEAs installation load is however not investigated.

Out of plane loading occurs after the anchor installation, typically in a damaged mooring line condition with a small number of mooring lines (typically 3), whereby the floater’s position changes with the mooring loads arriving at a different angle to the anchor in the horizontal plane. The effect of out of plane loading has been studied in soft clay soil conditions (Aubeny et al., 2011), (Aubeny, 2017) but again only limited work has been done for DEAs in non-cohesive soil (Davidson, 2023).

Developments for floating renewable energy are generally focussed on shallow waters (water depth up to 200 m) in which the most likely seabed is expected to be sandy. The available knowledge shows the DEA as suitable for uplift and out of plane loading in both cohesive and non-cohesive soils conditions, although there is only limited data available on DEA performance in non-cohesive soils. The tests described in the paper are designed to improve the validity and suitability of DEAs for uplift and out of plane loading in non-cohesive seabed conditions.

2 TEST SETUP

2.1 Testbed

For the execution of the tests, the test bed in ORE Catapult's FLOWIC facility in Aberdeen was chosen. The dimensions of the test bed are 6.0 m (*L*) by 2.0 m (*W*) by 1.3 m (*H*). The test bed was filled with 0.8 m of dry silica sand (14/25 sand according to a standard commercial specification (Aggregate, 2013)). The sand was poured into the test bed from the storage container, resulting in a loose to medium dense compaction. Before each test it was racked to provide a level surface. The winch for pulling in the DEAs has a maximum pulling capacity of 2 kN and a variable speed of 1 – 250 mm/s. During testing it was operated at a constant speed of 15 mm/s. A data acquisition system is used for the load monitoring during the tests and analysis post testing. Sample rate was 9 samples per second. A special load frame has been constructed to allow the different load angles to be applied. An image of the test bed is shown in Figure 1, with key components indicated.

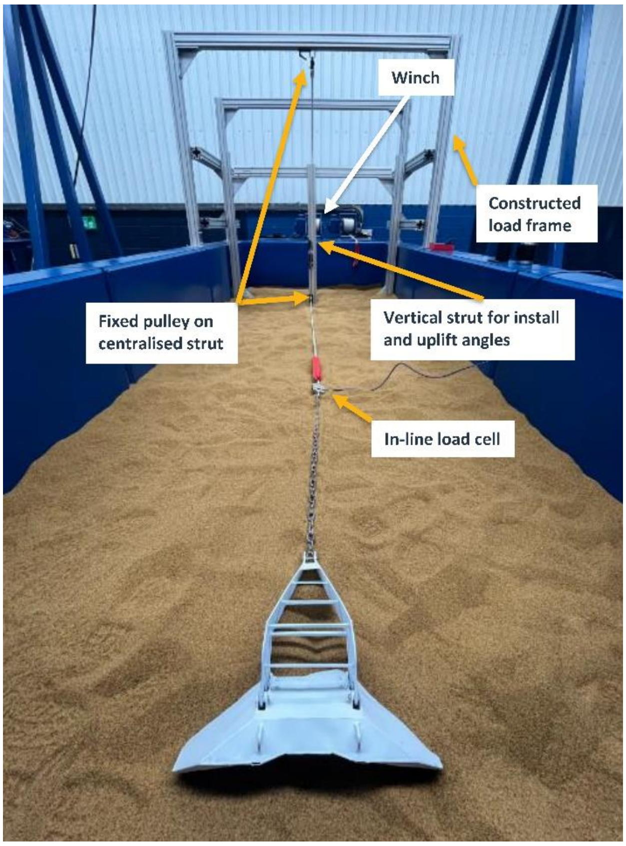

Figure 1. Anchor test rig

2.2 Anchor

For the tests, two different DEA models have been selected, the Mooreast MA5P and MA9P. Both are examples of DEAs that are currently used for offshore applications, both in oil and gas and renewable energy applications. For the test anchors, a nominal anchor size of 4.5 kg was selected, resulting in the anchor dimensions shown in Figure 2 and Figure 3. This size anchor was selected as it can be tested in the selected test bed, with full penetration and drag length achievable and within the winch capacity. The DEAs have been fabricated from stainless steel and are geometrically the same as the anchor sizes that are commonly used. For the sand soil conditions, the DEAs will be set to the recommended fluke/shank angle for sand, the smallest of the 3 available fluke/shank angles.

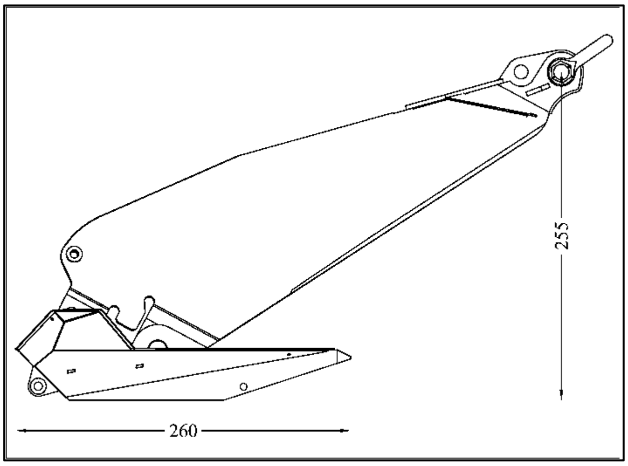

Figure 2. Side view of the Mooreast MA5P anchor with dimensions in mm

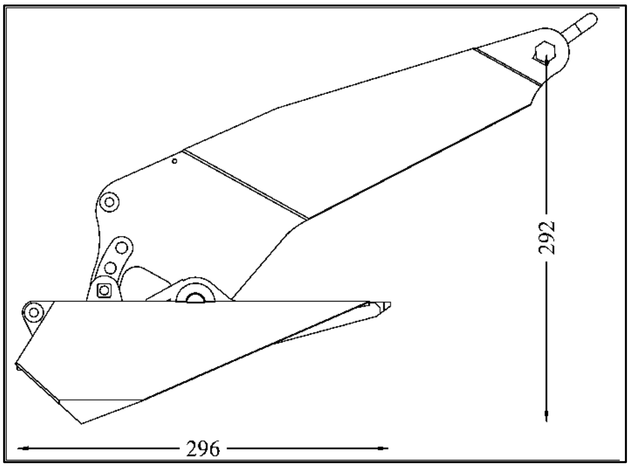

Figure 3. Side view of the Mooreast MA9P anchor with dimensions in mm

A picture of both DEA models in the test bed is shown in Figure 4. In non-cohesive soils, the anchor resistance is generate by the volume of soil mobilised in front of the anchor fluke, with the fluke generating most of the resistance. The main difference between the Mooreast MA5P and MA9P anchors is the shape of the fluke, with the Mooreast MA5P's fluke being mostly flat, while that of the Mooreast MA9P slopes downwards to the side, allowing for a larger volume of soil to be mobilised.

Figure 4. Both DEA models in the test bed

2.3 Planned Tests

The tests were planned to investigate the uplift and out of plane resistance of the DEA as well as the effect of the installation load on this resistance. For the uplift loading, the tests have been performed at 5 °, 10 °, 15 ° and 20 °. For the out of plane loading, the tests have been performed at 15 °, 30 °, 45 ° and 60 °. The uplift and out of plane tests will be performed at installation load levels equal to 50 %, 70 % and 100 % of the maximum capacity of the DEA in the test bed, when no uplift or out of plane loading is applied (0 ° test). For this purpose, the initial pull with the DEA will be the 0 ° test. This is a total of 12 uplift and 12 out of plane tests, excluding the 0 ° test. The test series were performed for both the Mooreast MA5P and Mooreast MA9P anchor models.

Each test consisted of pulling the DEA up to the required installation load, then stopping the winch, the load frame with the pulling wire set at the required angle (vertical or horizontal), after which the winch was started again until the peak resistance of the anchor was found. This resulted in two time versus pulling force series, one for the pull up to the installation load and one for the pulling in the required angular direction.

For each of the test series, the initial test to 100 % of maximum capacity and no uplift or out of plane loading was used as the reference point for determining the installation load for the subsequent tests (50 %, 70 % and 100 % tests). The drag length of the anchor was determined after pulling the anchor to the required installation load but before setting the load frame at the required angle, by measurring the distance between the initial position and the new position. The failure criterium for the applied uplift or out of plane loading was an additional anchor drag of 300 mm (1.15 fluke length of the Mooreast MA5P and 1.01 fluke length of the Mooreast MA9P anchor).

After each test the soil was racked to return it to a level surface and remove any potential influence of the previous anchor test trajectory on the new test. For example, the anchor being pulled through disturbed soil. The testing of the of the DEA to 100 % of the maximum capacity was performed at the beginning and end of each test day to ensure that no there where no significant differences in anchor performance.

3 RESULTS

3.1 General

A sample graph of the test results for the uplift loading at 10 ° is shown in Figure 5. The time versus tension series is shown for both DEAs and for both the installation pull and the uplift pulling. An image of one of the test DEAs fully embedded in the test bed is shown in Figure 6.

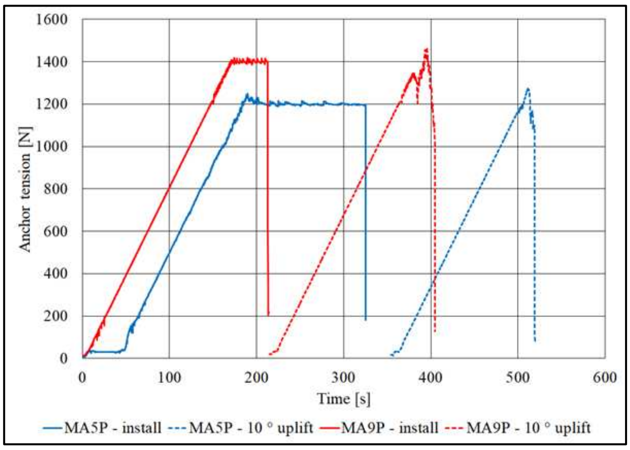

Figure 5. Sample graph of the test data

Figure 6. Image of fully embedded DEA

3.2 Uplift Loading

The uplift testing results are shown in Figure 7, together with three datapoints from Puech (1984). Note that for the MA5P model installed to 50 % of the maximum capacity, it was not possible to increase the uplift angle beyond 5 °, as this led to anchor failure in the soil. The horizontal axis shows the uplift angle. The vertical axis shows the measured force with uplift relative to the maximum force (1200 N for the MA5P model and 1400 N for the MA9P model).

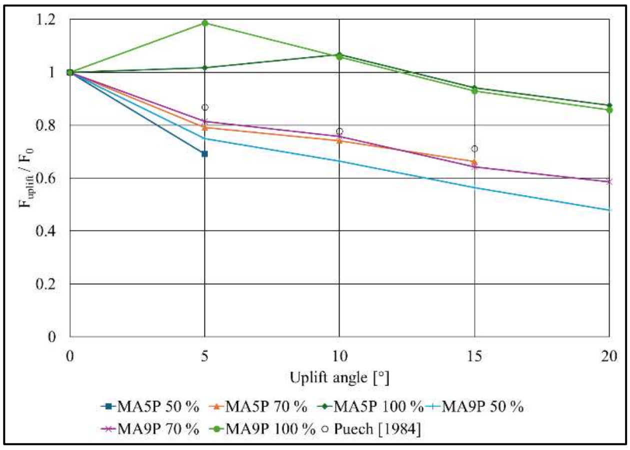

Figure 7. Uplift loading test results

The numerical data for the uplift testing of both DEA models is shown in Tables 1 and 2. The achieved results for the forces are shown relative to the maximum load achieved with 0 ° uplift (1200 N for the MA5P model and 1400 N for the MA9P model). The drag length measurement (horizontal displacement of the DEA) is given relative to the fluke length of the DEAs (260 mm for the MA5P model and 297 mm for the MA9P model). During each test the DEA model was fully embedded in the soil.

Table 1. MA5P uplift testing results

Installation load	Uplift angle	MA5P F_{uplift} / F_0	MA5P drag
100 %	0 °	1.00	7.6
50 %	5 °	0.69	1.5
50 %	10 °	-	-
50 %	15 °	-	-
50 %	20 °	-	-
70 %	5 °	0.79	2.8
70 %	10 °	0.74	2.8
70 %	15 °	0.66	2.7
70 %	20 °	-	-
100 %	5 °	1.02	6.5
100 %	10 °	1.07	8.4
100 %	15 °	0.94	6.3
100 %	20 °	0.88	6.7

Table 2. MA9P uplift testing results

Installation load	Uplift angle	MA9P F_{uplift} / F_0	MA9P drag
100 %	0 °	1.00	2.8
50 %	5 °	0.75	1.0
50 %	10 °	0.66	1.2
50 %	15 °	0.56	1.2
50 %	20 °	0.48	1.0
70 %	5 °	0.81	2.1
70 %	10 °	0.76	2.0
70 %	15 °	0.64	1.9
70 %	20 °	0.59	1.7
100 %	5 °	1.19	4.2
100 %	10 °	1.06	3.5
100 %	15 °	0.93	3.9
100 %	20 °	0.86	5.2

3.3 Out of Plane Loading

The results of the out of plane loading are shown in Figure 8. The horizontal axis shows the out of plane loading angle. The vertical axis shows the measured force with uplift relative to the maximum force (1200 N for the MA5P model and 1400 N for the MA9P model).

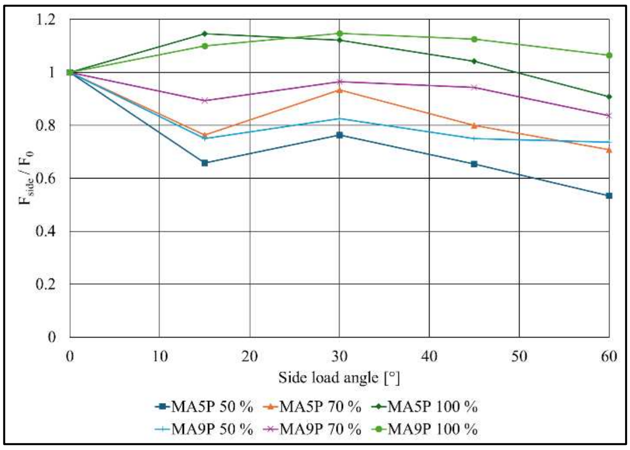

Figure 8. Out of plane loading test results

The numerical data for the out of plane load testing of both DEA models is shown in Tables 3 and 4. The achieved results for the forces are shown relative to the maximum load achieved with 0 ° out of plane load (1200 N for the MA5P model and 1400 N for the MA9P model). The drag length measured (horizontal displacement of the DEA) is given relative to the fluke length of the DEAs (260 mm for the MA5P model and 297 mm for the MA9P model). During each test the DEA model was fully embedded in the soil.

Table 3. MA5P out of plane loading results

Installation load	**Side load angle**	**MA5P F_{side} / F_0**	**MA5P drag**
100 %	0 °	1.00	7.6
50 %	15 °	0.66	1.7
50 %	30 °	0.76	1.5
50 %	45 °	0.65	1.4
50 %	60 °	0.53	1.5
70 %	15 °	0.76	2.9
70 %	30 °	0.93	3.0
70 %	45 °	0.80	3.1
70 %	60 °	0.71	2.6
100 %	15 °	1.15	5.3
100 %	30 °	1.12	5.2
100 %	45 °	1.04	4.8
100 %	60 °	0.91	4.2

Table 4. MA9P out of plane loading results

Installation load	**Side load angle**	**MA9P F_{side} / F_0**	**MA9P drag**
100 %	0 °	1.00	2.8
50 %	15 °	0.75	1.1
50 %	30 °	0.83	1.2
50 %	45 °	0.75	1.1
50 %	60 °	0.74	1.1
70 %	15 °	0.89	2.6
70 %	30 °	0.96	1.6
70 %	45 °	0.94	1.8
70 %	60 °	0.84	1.7
100 %	15 °	1.10	4.2
100 %	30 °	1.15	3.0
100 %	45 °	1.13	3.3
100 %	60 °	1.06	3.0

4 DISCUSSION AND CONCLUSION

Successful tests have been performed with model DEAs to investigate the effect of uplift and out of plane loading in non-cohesive soil (loose to medium dense sand).

With regards to the uplift resistance of the DEAs, the following can be concluded:

- The resistance against uplift increases with increased installation loads, this is due to deeper anchor penetration. At low installation loads, the MA5P model was not able to resist the higher uplift angles.
- The results at 70 % installation load compare well with earlier testing (Puech, 1984).
- At high installation loads, the uplift capacity exceeds the installation load for uplift up to 10 °.
- Both the MA5P and MA9P models show good uplift resistance for the range of uplift angles tested, with the MA9P model showing slightly better results, most likely due to the shape of the fluke and the larger volume of soil that is mobilised by the anchor.

With regards to out of plane loading, the following can be concluded:

- The resistance against out of plane loading increases with increased installation load, this is due to the deeper penetration into the soil.
- Compared to uplift loading, the effect of the out of plane loading on the DEA models is less.
- Peak out of plane loading resistance occurs around 30 ° out of plane loading, with a small reduction when the out of plane loading angle is increased.

Based on prior knowledge and the results of the testing program, DEAs are shown to be suitable for mooring systems with uplift and / or out of plane loading in cohesive and non-cohesive soils.

AUTHOR CONTRIBUTION STATEMENT

First Author: Conceptualization, Data curation, Formal Analysis, Writing- Original draft.
Other Authors: Supervision, Writing- Reviewing and Editing,

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