Experiment aided development of a hybrid mooring and foundation concept for marine energy applications

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ABSTRACT: In this work, the authors present a hybrid gravity-embedment mooring and anchoring solution for the safe and cost-effective station keeping of offshore renewable devices in soft seabed conditions. This is constituted by a series of clump weights of variable mass and size, interconnected through sections of synthetic material. The present study aims at investigating the holding capability of a 1:15 scale single mooring leg in controlled conditions. Tests are conducted in a current flume equipped with a sediment pit, and loads measured by means of a purpose-built frame with pulley and winch. A series of trials testing different configurations of the mooring line is used in order to optimize the design parameters and derive suggestions for future improvements. The paper presents and discusses the failure mechanisms and the failure loads which indicate the holding capability of the proposed design. The study will be of interest to researchers and practitioners considering hybrid mooring configurations.

1 INTRODUCTION

Moorings and foundations are important components of marine renewable energy installations. They have to guarantee the secure station keeping of the device without interfering with the operating requirements of each specific technology. To this purpose, a number of factors like environmental loads, location characteristics and legislative constraints have to be taken into account. The designs also have to be cost-effective, taking into account lifecycle operating conditions, to maximize the profitability of the project. There is a well-developed body of literature describing mooring and foundation concepts for the offshore renewable industry, some key references are briefly reviewed in the following.

A catalogue of mooring and foundations types specific for marine energy devices was produced within the EU project RiaSoR (EMEC 2016). Here, strengths and weaknesses of twelve mooring configurations and three foundation classes are analyzed together with their common failure modes and suitability to different regimes. Similarly, a “Mooring and Foundation Landscaping Study” (TTI 2018) was commissioned by Wave Energy Scotland in order to investigate current solutions and innovation opportunities in moorings and foundations for wave energy converters (WECs). The study identified ten different classes of mooring systems, and concluded, among other things, that solutions from other marine sectors (e.g. shipping) are not always transferable to WECs, highlighting the need for innovation. Another finding was that bulk material cost and heavy weight are among the main disadvantages of gravity-based anchors, with repercussions on installation costs. Another report (Weller et al. 2014) extended the review of existing mooring and foundation technologies used in the offshore industry by considering also the design tools and software currently available for the design of these systems. These include software packages for the analysis of offshore marine systems to capture the dynamic of moorings, as well as tools for the analysis of geotechnical structures to predict the capabilities of anchors and foundations. However, according to the report, standardized anchor selection tools do not currently exist, and the anchors selection is often based on engineering experience and the in situ soil conditions. An example of field testing to demonstrate the potential for a dynamic penetration model and predict the final anchor embedment depth is provided in O’Loughlin et al. 2016.

Under these premises, this paper presents the experimental development of a flexible and cost-effective mooring and anchoring solution for offshore renewable devices. This work is part of a wider study (Rinaldi et al. 2020), which focuses on the design of a modular mooring system for large commercial vessels in commercial harbors. This arrangement, shown in

Figure 1, involves the use of a series of mooring lines, made of synthetic material (Dyneema SK78, (Bexco catalogue 2019)), asymmetrically distributed around a central steel ring. The ring is connected to the marine energy device (in

Figure 1 this is an assumed floating offshore wind platform) by means of a 4″ studless chain. The mooring line sections are interconnected via clump weights of different sizes and masses, increasing from the center of the arrangement to its extremities, resulting in a catenary shape when the weights are lifted in response to the motions of the device. Once the weights are lifted, the restoring force due to gravity tends to bring the device back to its initial position. The number, distribution and separation of the mooring lines, as well as the number of clump weights, can be varied depending on the main direction and intensity of the incoming loads and other environmental conditions at site. For instance, in the example in

Figure 1, the main direction of the environmental loads is the lower-right corner. This modularity makes the proposed configuration extremely adaptable to a high number of offshore renewable technologies and environments.

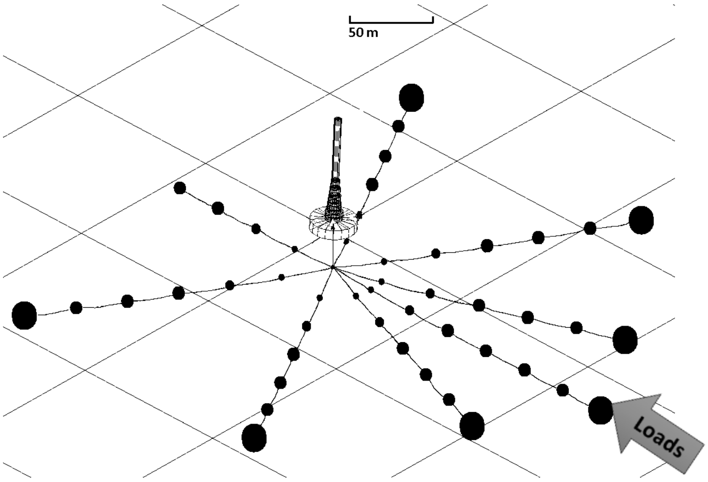


Figure 1. Representation of the implemented mooring system with a fictitious floating platform connected. Lateral view. Modelled using the software OrcaFlex.

The use of clump weights in mooring systems has been already investigated in literature (Ji,Yuan, and Chen2011; Ji and Yuan 2015; Yuan, Incecik, and Ji 2014). The main reason to use them is the reduction of vertical loads at the end of the mooring lines, up to the point of obtaining purely horizontal loads if a sufficient number of weights are used. This, in turn, reduces the uplifting forces on the anchors, reducing holding requirements and therefore size and cost of the foundations. In this way, cheaper alternatives to bulky and costly embedment or suction anchors can be proposed.

Nonetheless, once the validity of the overall mooring system has been proved both numerically and experimentally (Rinaldi et al. 2020), a suitable anchor arrangement for the ends of the mooring lines must be engineered. As such, this paper focuses on the design and development of a novel hybrid foundation to use the modular mooring system in marine energy applications.

The rest of the manuscript is organized as follows. In section 1.1 the proposed anchor concept is introduced. In section 2, the methodology to test the concept and obtain indications on its effectiveness is described. In section 3, the results of testing activities are provided, and section 4 discusses them in view of their scalability and design for marine renewables. Finally, in section 5, conclusions on this investigation are drawn together with indications for future work.

1.1 *Hybrid anchor concept*

The design proposed for this work is a hybrid gravity-embedment anchor. The main design intentions behind this concept are following an integrated mooring design approach: i) the use of cheap and easy to handle components, ii) possible to install and maintain by means of small vessels, and iii) system can be re-arranged depending on different configurations and constraints.

The design includes a gravity element, a granite block, mounted on top of a spike-type anchor, which provides penetration and embedment properties in soft seabeds (e.g. sand, silt or clay). The spike is constituted by a set of two triangular blades interconnected (welded) with each other. A picture representing the 1:15 scale model of this anchor is shown in Figure 2.

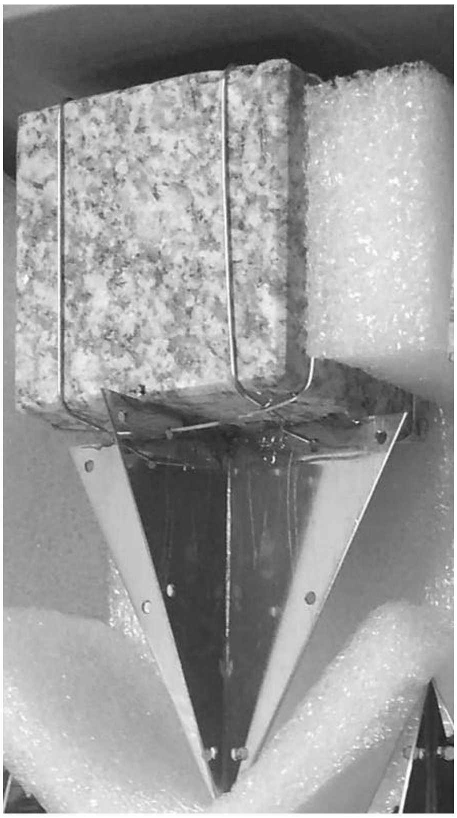


Figure 2. 1:15 scale model of the hybrid anchor design proposed.

Granite has been used due to its wide availability at a relatively low cost in the south-west of the UK, where the system has been originally designed. However, alternative shapes or materials could be considered depending on location or other constraints. Three small holes were drilled in each of the anchor blades that allow for the connection with other anchors or parts of the mooring system, described in Section 2.

2 METHODOLOGY

In order to verify the effectiveness of the anchor design proposed, a series of experimental tests have been conceived and executed. The objectives were the identification of areas for improvement and indications to fully satisfy the station-keeping requirements. The experiments involved the test of a single mooring leg, including a series of different connections for the anchors, in a sediment pit, filled with 0.25mm grain size sand, embedded in a current flume filled with water. This test rig is graphically represented in Figure 3.

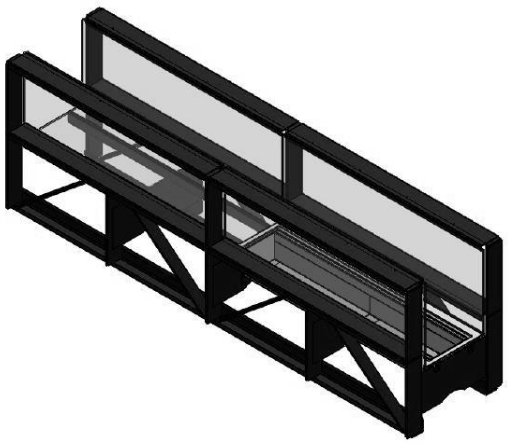


Figure 3. Section of the current flume, with embedded sediment pit, used for experimental tests. Courtesy of Plymouth University – COAST laboratory.

In order to evaluate the holding capacity under different configurations, a mooring leg comprising five clump weights of different sizes (3 big, 1 medium, 1 small; dimensions according to 1:15 Froude scaling for 4, 3 and 2 tons granite blocks respectively) is tested in the current flume. All dimensions and results in this paper are presented at experimental scale. The clump weights are connected via synthetic rope. The anchors were positioned in the sediment pit at one end of the mooring line. At the opposite end, known loads are applied by pulling from a floater through a pulley and winch system. This experimental setup is shown in Figures 4 and 5. Once the flume is filled with water, the mooring line describes a catenary, i.e. a parabolic arch, thus it is possible to pull the floater in order to stretch the mooring line and drag the anchors.

The main objectives of this series of test were to:

- Establish how the overall holding capacity of the proposed solution varies with the number of interconnected anchors;
- Establish the optimal connection point between two consecutive anchors;
- Establish the optimal distance between two consecutive anchors;
- Understand the anchors failure mechanism in order to propose ameliorative solutions.

The tests were sub-divided in three stages:

1. Test of the mooring leg connected to a single anchor. Varying connection point between anchor and smallest clump weight;
2. Test of the mooring leg connected to two anchors. Distance between anchors to be varied. Once the best (resisting the highest loads) distance is found, the point of connection between anchors is varied as described in stage 1.
3. Test of three, four and five interconnected anchors. Mutual distances and connection points between anchors are selected according to the best results of the above tests.

In the cases with multiple anchors, these are connected to each other by means of small chains and s-hooks placed in the holes in the blades. The failure loads of the anchors under different configurations are measured using masses of known weight. These are added on a built-for-purpose frame at increments of 0.01 kg until failure is achieved. The failure weight is considered the one causing the anchor blades to be fully extracted from the sediment and dragged from their initial position, making them incapable to resist any further loads. All tests are recorded until the moment of failure, and the failure load noted together with the direction towards which hybrid anchors rotate.

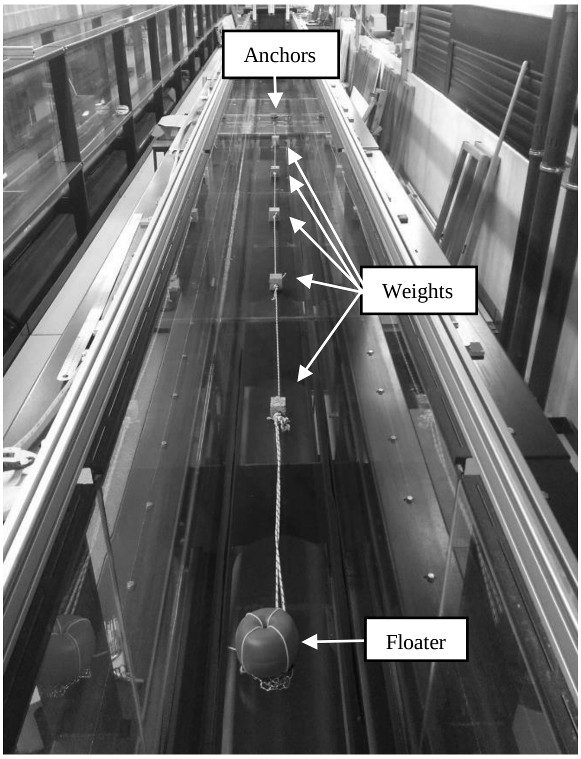


Figure 4. Section of the current flume used for the experimental tests. Anchors are embedded in the sediment pit at the far end of the picture. The floater from which the loads are applied is in the foreground. Clump weights are in between.

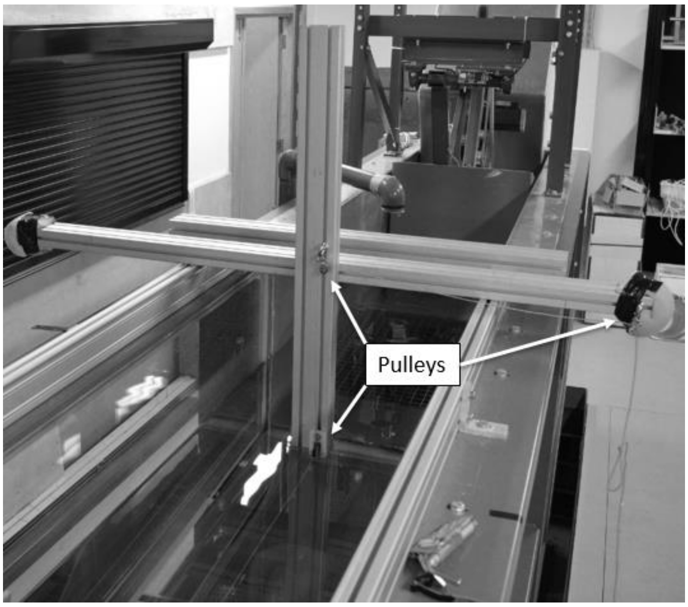


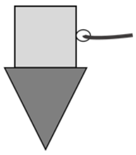
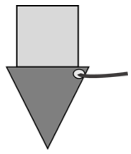
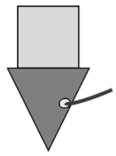
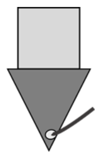
Figure 5. Picture of the frame containing the pulleys. A string is used to apply the weights of known mass needed to pull the mooring line during the tests.

3 RESULTS

The full outcomes for all the configurations tested during the experiments are shown in Tables 1-5. Each of the tested configurations is graphically represented in the first column. In particular, the drawings show the connection points selected for each trial. Failure loads and failure directions are provided in subsequent columns. The failure load is presented as the average weight in kilograms needed to fail (i.e. pull) the anchor arrangements. Measurements have been repeated between three to five times for each configuration (depending on the relative variation between consecutive measurements), and the average value selected.

The failure direction indicates the sense of rotation of the anchors during failure: a counterclockwise arrow indicates a rotation towards the end of the mooring line where the anchors are situated; a clockwise arrow indicates a rotation towards the opposite end (i.e. from which the load is applied). The second column (“spacing”) indicates the mutual distance between two consecutive anchors.

Table 1. Outcomes of the experimental tests with one single anchor.

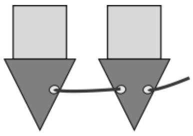
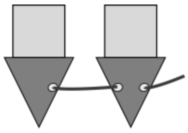
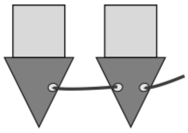
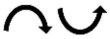
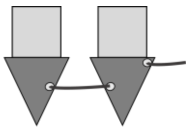
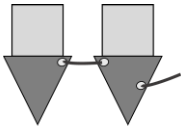
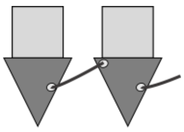
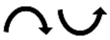
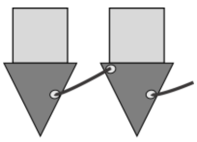
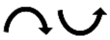
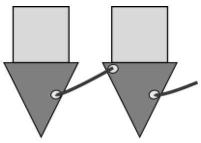
Connection	Spacing [cm]	Average Failure load [kg]	Failure direction
	N/A	2.61	
	N/A	3.30	
	N/A	3.85	
	N/A	3.37	

When the single anchor is tested, the point of connection between the anchor and the smallest clump weight (rest of the mooring) is varied as follows: middle of the block, top of the anchor blade, middle of the blade, and bottom of the blade. The best connection point (for which the failure load, hence the anchor’s holding capacity, is the highest) is found to be the one in the middle of the blade. The maximum average load with the single anchor is found at 3.85 kg.

When two inter-connected anchors are tested, firstly the distance between them is varied. These distances were affected by the length of the s-hooks and chain sections used to connect the two anchors. The idea was to explore distances ranging approximately from one to three anchor widths (10cm to 30cm). However, this range was reduced down to

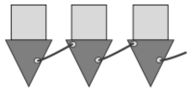
7cm, verifying that the shorter the distance between two consecutive anchors the better (the higher the failure load). Secondly, the connection points between the two anchors, as well as the one between the first anchor and the rest of the mooring line, were varied. The best connection points were found to be the middle of the blade in the direction of the coming load, and the top of the blade in the opposite direction. This is the configuration for which 7.56 kg of failure load (1.96 times the holding capacity of the single anchor) is achieved (see Table 2).

Table 2. Outcomes of the experimental tests with two interconnected anchors.

Connection	Spacing [cm]	Average Failure load [kg]	Failure direction
	25	5.80	
	15	6.36	
	7	6.48	
	7	5.50	
	7	6.60	
	7	7.56	
	15	6.56	
	8.5	6.85	

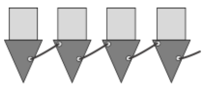
In terms of direction, the failure of the last anchor (with respect to the applied load) happens with the upper side of the block pitching towards the seabed (clockwise rotation), whereas the failure of the other anchor (the one connected to the rest of the mooring line) happens in the opposite direction (counterclockwise, with the lower tip of the anchor pitching towards the seabed). Therefore, solutions aiming at resisting these pitching motions should be added to the final design of the anchors in order to increase their holding capacity.

Table 3. Outcomes of the experimental tests with three interconnected anchors.

Connection	Spacing [cm]	Average Failure load [kg]	Failure direction
	8.5	9.52	

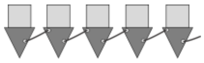
Once the best connection points are found and it is observed that reducing the mutual distance between two anchors is beneficial for the arrangement, tests are carried out to verify how the holding capacity increases with the number of anchors. It must be noticed that despite 7 cm was found as the best distance between two anchors, this is increased to 8.5cm for practical reasons related to the constituents of the connection chains. When three interconnected anchors are tested, the maximum average load is found at 9.52 kg (2.47 times the holding capacity of the single anchor). Apart from the pitching motion, also a moderate roll of the anchors is noticed, probably due to a constraint introduced by the connection chain between consecutive anchors. Again, a solution that adds resistance to these motions should be proposed to increase the holding capacity of the anchors.

Table 4. Outcomes of the experimental tests with four interconnected anchors.

Connection	Spacing [cm]	Average Failure load [kg]	Failure direction
	8.5	10.85	

Finally, when four and five inter-connected anchors are tested, the maximum average failure loads are found at 10.85 kg (2.81 times the holding capacity of the single anchor) and 11.55 kg (3 times the holding capacity of the single anchor) respectively.

Table 5. Outcomes of the experimental tests with five interconnected anchors.

Connection	Spacing [cm]	Average Failure load [kg]	Failure direction
	8.5	11.55	

The relationship between number of anchors and holding capability of the arrangement is shown in Figure 6. The trend suggests that the failure loads might have an asymptotic behavior, i.e. after a 2 anchors, the failure load (i.e. holding capacity) does no longer respond directly proportional.

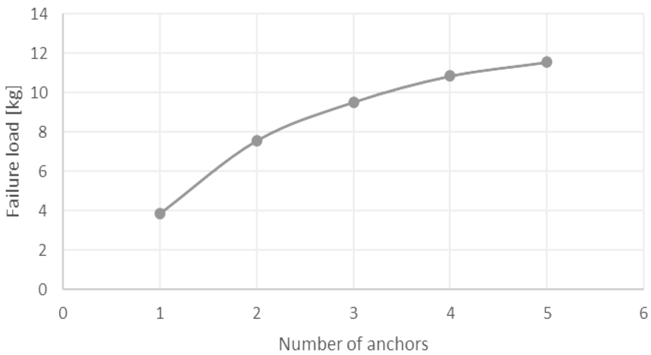


Figure 6. Relationship between failure loads and number of anchors for the scaled prototype.

4 DISCUSSION

The tests evaluating the failure mechanisms of the anchors permitted to establish a number of indications about the feasibility and future development of this hybrid and cost-effective foundation concept for offshore renewable devices. Firstly, as the number of aligned hybrid anchors increases, the holding capacity does not increase proportionally. Thus, a limited number of anchors (e.g. 2 to 3) might be a good compromise between costs and holding capability of the system. Secondly, the ideal connection points between two consecutive anchors have been identified. For reasons related to the motions of the anchors during failure, the best configuration is the one considering the middle point of the blade for the side of the anchor facing the rest of the mooring line and the one in the middle of the blade for the opposite side. Thirdly, a shorter distance between two consecutive anchors increases the holding capacity, which is a positive result because it permits to save material and costs.

By analyzing the anchors failure modes, two major suggestions for improvements can be made. Firstly, the shape of the blade beneath the granite block is considered. Since the anchor is dragged horizontally, the triangular shape of the blade can be modified in order to increase the area of the blade resisting the pull from the mooring line. This can be achieved by, for example, adding a rectangular frame or a skirt to the upper part of the spike. The second improvement addresses the failure movements of the anchors. Since these tend to rotate in different directions depending on their position in the mooring line, constraints between one anchor and the neighbor one, e.g. steel beams, could be implemented in order to keep them always horizontal and thus prevent the movements that lead to the failure of the anchors.

In order to assess whether the mooring and foundations arrangement proposed in this work are suitable for the application in the marine energy sector, the holding capacity required at the end of each mooring line is needed. This can be estimated by using numerical simulation software, e.g. Orcaflex. However, this is device and site specific. Although the holding requirement can be estimated, it must be noticed that fundamental theoretical and practical difficulties in scaling all the elements of the anchors, and especially of the environment, exist. For instance, the grains of sand could not be scaled down reliably using Froude scaling like the other components of the mooring arrangements. For this reason, the results on the failure loads cannot be reliably scaled up in order to estimate the holding capacity of the analogous full-scale system.

Besides, these failure loads are strictly related to the type and behaviour of sediment the anchors are embedded in, as such they may vary if a different or non-homogeneous sediment (differing to the one in the presented experiments) is considered. In this regard, the density, or better the void to fill ratio, of the sediment, plays a significant role in determining the holding capacity of the anchors. The denser (the more compact), the better (the higher the holding capacity). This phenomenon was also experienced during the experimental tests, since the sediment had to be manually re-compacted in preparation of each test. The anchors were fully embedded until the upper granite block is in contact with the sediment. Although the outcomes provided in Tables 1-5 show only the average failure load, repeated measurements under the same configuration provided slightly different failure loads depending on the extent to which the sediment had been re-compacted and subsequent anchors' embedment depth. As such, a consistent compaction effort was sought during the experiments.

The results should also be interpreted in the context that during the tests the loads were applied in a quasi-static way, by slowly adding weights to the mooring line. Different holding capacities may be obtained with dynamic or repetitive loads (e.g. due to non-linear environmental loadings).

5 CONCLUSIONS

A simple, modular and cost-effective mooring system is proposed for application in the offshore renewable energy sector. Following a feasibility study on the effectiveness of the overall mooring arrangement, the work presented in this paper focuses on the experimental verification of the anchors thought to provide the holding capacity required by the mooring lines. The experimental tests performed explored the functioning of the hybrid foundations, especially in terms of their failure mechanisms. As a result, design improvement measures in order to increase the holding capability of the anchor foundations have been identified. These include modifications to the current design and addition of novel elements, but do not neglect possible radical changes to the design. An example could be the inclusion of more anchors on a single platform equipped with a skirt to increase resistance to drag, as well as a shape of the blades modified according to the improvements discussed in the previous section. Further to the engineering considerations, all future decisions on the number and type of anchors will have to be weighed against economic and environmental constraints. For this reason, both a life cycle assessment (LCA) and an environmental impact assessment (EIA) will be necessary to compare the proposed design against traditional mooring systems and measure the impact on the environment respectively.

All these findings are especially important in view of the next stage of this concept development, which will consist in the trial of a single full-scale mooring leg before, possibly, testing a full-scale mooring system. In fact, tests at full scale would allow for the quantification of the actual holding capacity of the anchors for the modular mooring leg. In this regard, although it is not possible to estimate the full-scale failure loads from prototype testing, it is advisable to repeat scaled tests after the implementation of the enhancements identified in this work, in order to obtain a comparative estimate of the improvements before proceeding with more expensive full-scale tests.

In conclusions, the experimental tests in the development of a novel mooring and foundation design have demonstrated the feasibility of the design concept and provided important information regarding the design parameters and potential design improvements. The further development of this hybrid concept has the potential to provide cost-effective station keeping.

ACKNOWLEDGMENTS

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