# Summary of the MSLWEC Project

*M7 & WP6*

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DEPARTMENT OF CIVIL ENGINEERING
AALBORG UNIVERSITY

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Department of Civil Engineering
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by

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# Preface

The present report summarizes all work conducted in the EUDP project *"Mooring Solutions for Large Wave Energy Converters"* (MSLWEC) running in the period June 2014 - July 2018. The project aimed at improving the mooring design for large floating wave energy converters, using four Danish devices as case studies: Floating Power Plant, KNSwing, LEANCON Wave Energy and Wave Dragon. This report concludes the project and covers the final *"Milestone 7: Summary of Findings and Project"*. While most of the work presented in this report has already been published in other publications, some new information and findings are present and, therefore, the report is part of *"Work Package 6: Selection and Results"*.

The report is produced by Aalborg University, while the project work has been performed in a cooperation with all the partner WECs, Tension Technology International (TTI) and Chalmers University of Technology.

For further information and questions regarding the content of the report and the MSLWEC project, please contact Jonas Bjerg Thomsen (jbt@civil.aau.dk) from Department of Civil Engineering.

Aalborg University, June, 2018

# Contents

# Introduction

The present report summarizes the Danish research project *"Mooring Solutions for Large Wave Energy Converters"* (MSLWEC), which was running from June 2014 to July 2018.

The project was initiated due to the relatively large number of floating WECs in the Danish wave energy sector. All of these have a critical need for a mooring system to ensure station keeping and had so far based the mooring design on known experience from the offshore Oil & Gas (O&G) sector. Still, many different solutions had been proposed. However, WECs have very different characteristics and their deployment sites are different from those of O&G structures. Consequently, and due to insufficient design approaches, many mooring failures had already been experienced, while also the cost had been seen to be generally high.

The MSLWEC project has addressed these topics and, thereby, reduced cost of mooring and increased their durability. The project focussed on large floating WECs for which similar characteristics could be expected: the use of passive moorings and deployment in shallow to intermediate water depths. Consequently, four Danish WECs were selected for analysis. In addition, one company specialized in mooring design and synthetic ropes were included in the project, together with two universities with great experience in numerical modelling and mooring research. Combined, the project consortium consisted of seven partners:

1. Aalborg University, Department of Civil Engineering, Denmark.
2. Chalmers University of Technology, Sweden.
3. Tension Technology International (TTI), United Kingdom.
4. Floating Power Plant, Denmark.
5. KNSwing, Denmark.
6. LEANCON Wave Energy, Denmark.
7. Wave Dragon, Denmark.

The project aimed at providing experience and guidelines in mooring design and solutions. The results have been significantly disseminated in a variety of publications as will be described in Chapter 7. The full list of publications can be found in the References and will also be listed in the following chapters.

The work of the MSLWEC project was divided into seven work packages. This report will shortly summarize the findings and conclusions from the project and the work, and, consequently, the report is divided into nine chapters including this Introduction. The following chapters will each present a work package and the related work, before the final chapter summarizes and concludes the project, while addressing the defined milestones. For detailed description of the findings in the project work, the reader is referred to the actual publications.

# WP1: Design Practice and Tools

Work Package 1 provided the initial baseline for the MSLWEC project. The objective of the Work Package was to provide an initial understanding of the design procedures and mooring layouts currently used by the WEC developers in Denmark. In addition, it aimed at providing an initial definition of the required design procedure and tool to be used in the coming mooring analysis and design.

The following publications are direct output of Work Package 1:


[1] Jonas Bjerg Thomsen, Francesco Ferri, and Jens Peter Kofoed. Assessment of Current State of Mooring Design in the Danish Wave Energy Sector. In *Proceedings of the 11th European Wave and Tidal Energy Conference EWTEC2015*. Technical Committee of the European Wave and Tidal Energy Conference, 2015

[2] Jonas Bjerg Thomsen, Francesco Ferri, and Jens Peter Kofoed. *Current Mooring Design in Partner WECs and Candidates for Preliminary Analysis: CM1 & M3*. Aalborg University, Department of Civil Engineering, 2016. Confidential report

[3] Jonas Bjerg Thomsen, Francesco Ferri, and Jens Peter Kofoed. Screening of Available Tools for Dynamic Mooring Analysis of Wave Energy Converters. *Energies*, 10(7), 2017

[4] Jonas Bjerg Thomsen, Claes Eskilsson, and Francesco Ferri. *Assessment of Available Numerical Tools for Dynamic Mooring Analysis: WP1.2 & M1*. Department of Civil Engineering, Aalborg University, 2017


## Task 1.1: Current Mooring Design in Partner WECs

*The objective in Task 1.1 was to achieve an understanding of the mooring design at the beginning of the MSLWEC project to form a baseline for the continuing work.*

In both [1] and [2], the initial state of the mooring design for the four partner WECs were investigated. It was evident that many of the early stage mooring designs were based on experience from the O&G sector and consisted of mooring chain and layouts such as catenary anchor leg mooring (CALM) system, single anchor leg mooring (SALM) system or catenary turret systems. By then, some devices had considered more novel solutions consisting of synthetic nylon lines.

The study illustrated how none of the mooring solutions could be considered final solutions, since they did not satisfy design standards and had many variations in the applied design procedures. A critical shortcoming was illustrated in the included environmental loads in addition to no consideration of design limit states and a general use of static analysis to estimate mooring and WEC response. In addition, the work provided an initial cost estimate of the current mooring designs, which will be presented in later chapters.

## Task 1.2: Assessment of Available Numerical Tools for Dynamic Mooring Analysis

*The objective of Task 1.2 was to asses available tools for numerical analysis in order to allow for the selection of tool to be used in the rest of the project.*

Many different tools are available for numerical analysis of mooring and WEC response. In [3, 4], the MSLWEC project investigated a number of these in order to find a suitable software package for analysis of moorings for large WECs. The objective was to ensure that the capabilities required by design standard were present so that the mooring solutions can be certified by one of the certification companies. In [3], the software packages DeepC and OrcaFlex were selected and compared for a case relevant to the MSLWEC project. The results showed good agreement, but DeepC provided several shortcomings, while OrcaFlex had no apparent drawbacks, is widely used in the industry and, therefore, easy for certification bodies to accept. Consequently, OrcaFlex was selected for further analysis.

## Task 1.3: Load Estimation Methodologies

*The objective of Task 1.3 was to provide an understanding of the loads on large WECs and the procedures required for assessing them.*

Methodologies to estimate environmental loads on large floating WECs and their moorings were investigated and described in several of the publications [1, 3, 5–10]. All work in the MSLWEC project was centred on the boundary element method (BEM), which invokes the linear potential flow theory. The further work was focussed on initial simplified methodologies like quasi-static frequency domain analysis [5, 8] to more sophisticated full dynamic time domain analysis in [7]. In [9, 10], the methodologies were compared and will be described later in this report. A considerable shortcoming was identified in the estimation of loads on an overtopping WEC like the Wave Dragon when using BEM. Some work has by now been put into improving the method of estimating wave loads on such a structure and will be published in later research.

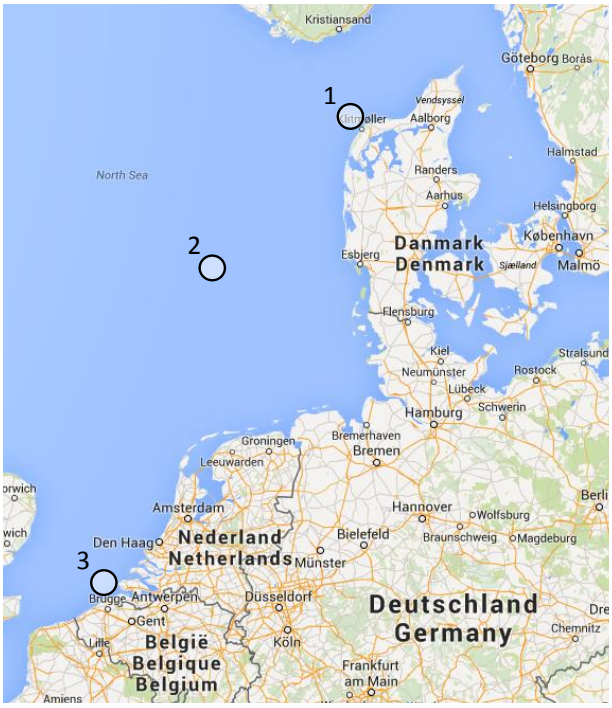
# WP2: Mooring Cases

Throughout the project, the objective was to design optimal mooring solutions for each of the partner WECs. The initial mooring designs found in WP1, had been developed to given sites (despite the mentioned shortcomings) and the project aimed at improving the mooring designs for those specific locations. Work Package 2 was aimed at defining these locations and identify the potential mooring solutions to consider in the remaining project. The outcome of Work Package 2 is published in the following publication:

[2] Jonas Bjerg Thomsen, Francesco Ferri, and Jens Peter Kofoed. *Current Mooring Design in Partner WECs and Candidates for Preliminary Analysis: CM1 & M3.* Aalborg University, Department of Civil Engineering, 2016. Confidential report

## Task 2.1: Definition of Main Parameters and Ranges

*The objective of Task 2.1 was to provide a description of the environmental conditions for selected deployment sites for the partner WECs. The locations was intended to provide a case study for each device to use throughout the project.*




Planned deployment sites for the four partner WECs. (1) LEANCON and Wave Dragon, (2) KNSwing and (3) Floating Power Plant. Adapted from [2].

Each of the partner WECs were planned for deployment at one of the three pre-decided locations illustrated in the figure above.

According to design standards and other studies, it had been proved that the extreme cases were defining for the overall mooring cost and, naturally, determining for survivability. Following the requirements in design standards, the extreme sea states were defined including wind, wave, current and sea level rises.

## Task 2.2: Definition of Mooring Solutions Candidates

*The objective of Task 2.2 was to provide an overall description of the mooring solutions that were considered relevant to investigate in the MSLWEC project.*

Based on the initial mooring solutions identified in Work Package 1, similar solutions were selected in [2] as potential mooring solutions to consider in the project. This included:

1. A CALM system, consisting of mooring chains and a CALM buoy.
2. A turret system consisting of mooring chains.
3. A single point mooring (SPM) system consisting of synthetic lines and a SPM buoy.
4. A turret system consisting of synthetic lines.
5. A SALM system consisting of a steel tether and synthetic lines.

The CALM and turret system with chain lines are traditional mooring solutions known from the O&G sector, while the use of synthetic lines, particularly nylon, are more novel solutions. Consequently, the SPM system and synthetic turret are similar in layout compared to the CALM and chain turret, with the exception of line materials. It was decided in the MSLWEC project [2] that both traditional and novel solutions should be investigated. The SALM system were identified as a novel solution for permanent moorings and hence, were selected for continuing analysis.

# WP3: Preliminary Analysis

Based on the defined mooring solution candidates and the relevant deployment sites, Work Package 3 aimed at screening the solutions and investigate their potential.

The work in Work Package 3 is published in the following publications:


[11] Jonas Bjerg Thomsen, Jens Peter Kofoed, Martin Delaney, and Stephen Banfield. Initial Assessment of Mooring Solutions for Floating Wave Energy Converters. In *The 26th International Ocean and Polar Engineering Conference ISOPE2016*. International Society of Offshore and Polar Engineers, 2016

[8] Jonas Bjerg Thomsen and Martin Delaney. *Preliminary Analysis and Selection of Mooring Solution Candidates: M4 & WP3*. Department of Civil Engineering, Aalborg University, 2018


## Task 3.1: Quasi-Static Analysis of Mooring Solution Analysis

*The objective of Task 3.1 was to use quasi-static analysis to make an initial mooring design for each of the partner WECs, using the selected mooring solutions candidates.*

The quasi-static analysis was described in [8, 11] and used to evaluate which mooring solutions that were most promising to consider in the rest of the project. A general conclusion was that use of chain material was insufficient in shallow/intermediate water depths for large WECs. Very high environmental loads were experienced, which required large chains with high strength, which, furthermore, resulted in high mooring stiffness and resulting large mooring loads. The solutions were only possible when using unrealistically long mooring lines. On the contrary, synthetic lines were found highly useful both in terms of providing high compliance and smaller loads, while also reducing the seabed footprint.

## Task 3.2: Check of Mooring Solutions Candidates for Buildability

*The objective of Task 3.2 was to describe the buildability of the mooring solution candidates in order to highlight drawbacks and advantages for each, considering construction, installation, O&M and decommissioning of the solutions.*

In [8], a buildability analysis of each mooring solutions candidate was performed. Problems related to the large mass of chain solutions were highlighted, while the low mass of synthetic lines was identified as a potential cost reduction driver in all parts of mooring and its operation. Considerations and solutions related to turrets, mooring buoys etc. were described in details in [8].

## Task 3.3: Selection of Final Mooring Solution Candidates for Full Dynamic Analysis

*The objective of Task 3.3 was to select a mooring solution concept for each partner WEC to be analysed and designed in the rest of the project.*

Based on the outcome of Task 3.1 and 3.2, the developers of the partner WECs selected a mooring solution concept for their device. The selection took place during a workshop as described in [8]. In general, it was decided that the remaining MSLWEC project should consider synthetic nylon rope solutions, due to their advantage over chains, while different layouts were selected for the devices:

| **WEC** | **Mooring Solution** |
|---|---|
| Floating Power Plant | Synthetic turret system |
| KNSwing | Synthetic turret system |
| LEANCON | Synthetic SALM system |
| Wave Dragon | Synthetic SPM system |

# WP4: Full Analysis

Based on the selected mooring solutions and the defined design cases, Work Package 4 aimed at making a full analysis and design of each mooring solution using the tools investigated in Work Package 1. The work aimed at finding optimal solutions, which both secured that the moorings were reliable and capable of being certified, but also had a high level of cost efficiency. The work in the present Work Package conformed a large part of the overall MSLWEC project and has been published in the following publications.


[12] Jonas Bjerg Thomsen and Francesco Ferri. *Full Dynamic Analysis of Mooring Solution Candidates - First Iteration: T4.3 & M6.* Department of Civil Engineering, Aalborg University, 2017

[5] Jonas Bjerg Thomsen, Francesco Ferri, and Jens Peter Kofoed. Experimental Testing of Moorings for Large Floating Wave Energy Converters. *Progress in Renewable Energies Offshore RENEW2016*, 2016

[6] Jonas Bjerg Thomsen. *Validation of Mean Drift Forces Computed with the BEM Code NEMOH.* Department of Civil Engineering, Aalborg University, 2017

[7] Jonas Bjerg Thomsen, Francesco Ferri, and Jens Peter Kofoed. Validation of a Tool for the Initial Dynamic Design of Mooring Systems for Large Floating Wave Energy Converters. *Journal of Marine Science and Engineering*, 5(4), 2017

[13] Jonas Bjerg Thomsen. *Hydrodynamic Models of Partner WECs: T4.3.* Department of Civil Engineering, Aalborg University, 2018

[9] Jonas Bjerg Thomsen, Francesco Ferri, and Jens Peter Kofoed. *Experimental Testing and Validation of Selected Tools for Mooring Analysis: M5, T4.1 & T4.2.* Department of Civil Engineering, Aalborg University, 2018

[14] Jonas Bjerg Thomsen, Francesco Ferri, Jens Peter Kofoed, and Kevin Black. Cost optimization of mooring solutions for large floating wave energy converters. *Energies*, 11(1), 2018. The article is published in a Special Issue of Energies, "Wave Energy Potential, Behavior and Extraction"


## Task 4.1: Creation/Acquisition of Lab. Data for Validation/Calibration

*The objective of Task 4.1 was to create a database of experimental data to be used for validation of the numerical tools.*

As a representative case study, the Floating Power Plant WEC was selected for use in a two month test campaign at Aalborg University. As described in [5, 9], a simplified model of the device was constructed, disregarding the wind turbine and wave energy PTO. The device was tested in operational and extreme sea states, while motions and mooring loads were measured. The data was used to provide an initial understanding of the response of the structure and the influence of mooring stiffness and mass moment of

inertia. A key conclusion, as presented in [5, 9], is that a 60% reduction of the mooring line stiffness results in up to 50% reduction of the mooring loads, highlighting the great potential of very compliant mooring line materials such as nylon.

In addition to the two month test campaign at Aalborg University, the KNSwing was tested in Portaferry, Ireland in the project period, while the LEANCON WEC was tested offshore in scale 1:10 at Nissum Bredning.

## Task 4.2: Pre-Validation/Calibration of Selected Tools for Full Dynamic Analysis

*The objective of Task 4.2 was to use the acquired data from Task 4.1 to validate the numerical tools considered in the MSLWEC project.*

As presented, the partner WECs had utilized a quasi-static approach to design their initial mooring system. A similar approach was used in Work Package 3. In [5, 9], the experimental model was used to validate this approach, illustrating a clear insufficiency in applying the method for mooring design in extreme cases. An underestimation of mooring line loads of up to 50% was achieved, which formed a critical problem for the safety and reliability of the systems. Consequently, a full dynamic analysis was performed. In Task 1.2, such a tool was selected and by using the experimental model for comparison, an understanding of the dynamic numerical model was obtained. The model was based on results from the linear BEM and from time-domain simulations in OrcaFlex. In [6], the calculated drift coefficients from the BEM code were assessed and verified against analytical solutions.

It was clear from the dynamic model that damping was significantly underestimated in the model, but by using and describing a simplified methodology to evaluate drag coefficients, a model useful for initial design was obtained. Comparison of mooring line tensions illustrated an overestimation in the numerically determined results of up to 11%. In an initial design case, and to provide understanding of the mooring behaviour, this is acceptable. Especially, compared to the quasi-static approach where underestimations of the tensions were achieved. The full dynamic model still provided underestimation of linear damping, and it was illustrated how a significant improvement could be achieved by using experimental data (or higher order models like CFD) to calibrate the model. Due to the acceptable agreement between the experiments and numerical model, a similar methodology was considered applicable to the partner WECs.

## Task 4.3: Full Dynamic Analysis of Final Mooring Solution Candidates

*The objective of Task 4.3 was to apply the full dynamic analysis approach to analyse and design an optimal and reliable mooring solution for each partner WEC. The goal was to secure both cost efficiency and a certifiable mooring design.*

A numerical model was produced for each partner WEC in [13] and used to analyse the WEC and mooring response. As presented in [14], each mooring concept has a range of parameters, such as number of lines, line diameter etc., which could be varied in order to design the solution. The choice of parameter, naturally, affected both the mooring response and the corresponding mooring cost. In [14], a cost database was constructed defining the total lifetime cost as function of input mooring parameters. By utilizing this

database and the numerical model, it was possible to evaluate the mooring in terms of both response and cost. The number of possible mooring configurations for each concept was illustrated to be significant and finding the most cost-efficient solution, which also fulfilled the design requirement, were time-demanding as each configuration required a numerical simulation. Consequently, [14] illustrated the applicability of a surrogate-based optimization routine to find an optimum mooring configuration with only a limited number of evaluations of the numerical model. Additionally, the model had the benefit of providing information on how each parameter influenced the overall mooring cost, and allowed for manual evaluation of each solution in order to select those with highest safety.

By use of this methodology, an optimum mooring configuration was found for each device, still considering the selected concept in Task 2.2.

# WP5: Cost Evaluation

A key objective of the MSLWEC project was to find cost-efficient mooring solutions for the partner WECs. Work Package 5 was aimed at providing understanding of what parameters influenced the mooring cost and how the cost had developed throughout the project. Many of the key cost data are presently confidential and published as such in the following publications.


[2] Jonas Bjerg Thomsen, Francesco Ferri, and Jens Peter Kofoed. *Current Mooring Design in Partner WECs and Candidates for Preliminary Analysis: CM1 & M3.* Aalborg University, Department of Civil Engineering, 2016. Confidential report

[14] Jonas Bjerg Thomsen, Francesco Ferri, Jens Peter Kofoed, and Kevin Black. Cost optimization of mooring solutions for large floating wave energy converters. *Energies*, 11(1), 2018. The article is published in a Special Issue of Energies, "Wave Energy Potential, Behavior and Extraction"

[15] Kim Nielsen, Jonas Bjerg Thomsen, Francesco Ferri, Erik Friis-Madsen, Kurt Due Rasmussen, Sarah Thomas, and Jens Peter Kofoed. *Impact of Cost of Selected Mooring Solutions on CoE of Partner WECs: CM2 & WP5.* Department of Civil Engineering, Aalborg University, 2018. Confidential report

[16] Kevin Black, Stephen Banfield, James MacKay, Martin Delaney, Jonas Bjerg Thomsen, Francesco Ferri, and Jens Peter Kofoed. *Potential Cost Reduction Through Large Scale Production: CM3 & T5.3.* Department of Civil Engineering, Aalborg University, 2018. Confidential report

[17] Jonas Bjerg Thomsen and Morten Thøtt Andersen. Sensitivity and Cost Analysis of Mooring Solutions for Large Renewable Energy Structures. *The 37th International Conference on Ocean, Offshore & Arctic Engineering OMAE2018*, 2018


## Task 5.1: Evaluation of Cost of Mooring Solutions Applied to Partner WECs

*The objective of Task 5.1 was to develop cost estimations of the initial and optimized mooring solution for each partner WEC.*

An initial estimation of the cost of the mooring systems at the beginning of the project was published in [2]. Throughout the MLSWEC project, the understanding of the mooring cost was improved and hence, despite utilizing the same overall methodology at the initial and final cost estimates, the improved knowledge affected the comparison. The final mooring cost was described in [14] and found by utilizing the optimization routine to secure the identification of the most cost-efficient solutions.

Due to the different WECs and applied mooring solutions, a cost comparison between the different concepts were not possible. Consequently, a case study was performed in [17], which considered the same WEC and environmental conditions and used the

optimization routine to find the optimal solution for three different mooring concepts, which corresponded to those considered in the project. It was found that a synthetic SPM solution was cheapest, while the turret system was affected by a high turret cost and the SALM system was influenced by very high anchor cost. The latter was a result of use of a gravity-based anchor, which was proved to be insufficient in this case and, hence, provided an unrealistic high mooring cost.

The cost for all systems was highly affected by the given design conditions and can vary dependent on device and deployment site, meaning that other result can be obtained for other cases.

## Task 5.2: Impact of Cost of Mooring Solutions on CoE of Partner WECs

*The objective of Task 5.2 was to compare the cost of the initial and final mooring solutions for each WEC and evaluate the impact on LCoE.*

The report [15] provided a representative evaluation of the LCoE for each partner WEC, considering first the initial mooring layouts and, afterwards, the final mooring solutions. LCoE reductions in the range 10-30% were found resulting from several parameters. The most important are:

- Reduced mooring cost from a reduction of materials due to the more efficient and light nylon ropes.
- Reduced cost of installation and decommissioning due to lighter materials.
- Improved understanding of mooring cost, particularly on the O&M cost, resulting in a significant difference between initial and final estimations.

It is important to note that all the initial mooring solutions were designed using a static approach and not considering design standards and their required environmental loads, safety factors and return periods. Consequently, there was a great risk that the initial mooring solution could not survive in the design conditions and did not have a similar lifetime as the final. As a result, it was observed that part of the CAPEX cost for the LEANCON device was increased as a consequence of the MSLWEC project. However, this increase is required and desirable due to the improved reliability of the mooring system.

## Task 5.3: Evaluation of Potential Cost Reduction Through Large Scale Production

*The objective of Task 5.3 was to evaluate how a large scale production potentially could reduce the mooring cost identified in Task 5.2*

While the previous cost estimations in the MSLWEC project had been for a single device, Task 5.3 and [16] assessed the potential mooring cost reduction from mass production related to installation in a 200 MW WEC farm.

Expectedly, significant cost reductions were presented in [16] as a consequence of large scale production. Initial estimates stated that 33-46% cost saving could be expected. The most dominant factors were identified to be bulk discount on materials such as mooring lines, connectors and anchors, with the latter being the most dominant. It was stated how even more cost could be saved by future use of e.g. shared anchors and novel anchor and connection types.

# WP6: Selection and Results

Based on the found mooring solutions and the previous investigation into mooring analysis and design, Work Package 6 allowed for evaluation of pros and cons in each system considering e.g. sensitivity. Finally, based on the findings and work in the MSLWEC project, the work package aimed at defining parameters for future research and development. Work in this topic has been published in the following publications, while some of the discussion is only present in this present report.


[17] Jonas Bjerg Thomsen and Morten Thøtt Andersen. Sensitivity and Cost Analysis of Mooring Solutions for Large Renewable Energy Structures. *The 37th International Conference on Ocean, Offshore & Arctic Engineering OMAE2018*, 2018

[18] Guilherme Moura Paredes and Jonas Bjerg Thomsen and Francesco Ferri and Claes Eskilsson. *Mooring Design for Large WECs - A Reliability Analysis: T6.1.* Department of Civil Engineering, Aalborg University, 2018. Confidential report

[10] Jonas Bjerg Thomsen. *Mooring Solutions for Large Wave Energy Converters.* PhD thesis, 2017

[19] Jonas Bjerg Thomsen, Jens Peter Kofoed, Francesco Ferri, Claes Eskilsson, Lars Bergdahl, Martin Delaney, Sarah Thomas, Kim Nielsen, Kurt Due Rasmussen, and Erik Friis-Madsen. On Mooring Solutions for Large Wave Energy Converters. In *Proceedings of the 12th European Wave and Tidal Energy Conference EWTEC2017.* Technical Committee of the European Wave and Tidal Energy Conference, 2017

[20] Jonas Bjerg Thomsen and Francesco Ferri and Jens Peter Kofoed and Claes Eskilsson and Lars Bergdahl and Martin Delaney and Kevin Black and Stephen Banfield and James MacKay and Sarah Thomas and Kim Nielsen and Kurt Due Rasmussen and Erik Friis-Madsen. *Summary of the MSLWEC Project: M7 & WP6.* Department of Civil Engineering, Aalborg University, 2018


## Task 6.1: Sensitivity and Risk/Reliability for Selected Mooring Solutions

*The objective of Task 6.1 was to identify each mooring system's sensitivity to a number of parameters, and discuss risk and reliability concerns for all the solutions.*

The mooring systems were designed in Work Package 4 for a selected deployment site and its environmental conditions. For cost optimization, it was beneficial to design the system to utilize as much of the system strength as possible, but this, naturally, made the systems more vulnerable to uncertainties in the environmental conditions. In [17], the systems sensitivity to variations in selected environmental parameters were tested. Three different mooring systems (corresponding to those considered for the partner WECs) were designed and optimized for an identical structure and design conditions. It was followed by a number of evaluations of the design tension response with varying wave height, wave

period, water depth and current and wind velocity. All systems were found to be vulnerable to changes in the wave height with the SALM system being the most critical. Wave period, current and wind had less influence, while the water depth was illustrated to have an impact on only the turret system.

In [7], the systems sensitivity to the number of lines were additionally evaluated. Many previous concepts have been designed with three mooring lines, but it was illustrated how a failure of a single line resulted in a significant loss of strength in the total system and a critical offset of the structure. By just applying four lines, a considerable improvement was observed. The analysis conformed a simple analysis in the accidental limit state (ALS), were a single line is removed and the response is verified. Consequently, the MSLWEC project only considered solutions with more than three lines (except in the SALM system). This also meant that the SPM and turret system had more desirable redundancy, while the SALM system, naturally, is more vulnerable to failure of a line. In the considered SALM case, four lines connected the WEC to the single mooring leg, meaning that some redundancy was present, but the system was still only connected to the seabed through a single line, providing a critical point.

In [18], the Floating Power Plant was used as case study for an analysis of the potential use of a stochastic design approach instead of the deterministic approach based on safety factors, which was used earlier in the project and in traditional mooring design. The design of the mooring system was assessed by considering the uncertainties in both structural and environmental parameters such as line stiffness and water depth. The work was done in collaboration with the EU project MoWE.

## Task 6.2: Evaluation of other Pros and Cons for Selected Mooring Solutions

*The objective of Task 6.2 was to make a final evaluation of the advantages and drawbacks of each system.*

While the MSLWEC project had illustrated that the selected mooring systems could be designed for the partner WECs in accordance with a selected design standard, the project had also identified difficulties and differences in the systems. As presented in Task 6.1, the mooring systems all have a certain sensitivity to environmental changes, but it is critical to note that the turret system is vulnerable to water depth changes and will experience higher loads and a much different response if the depth is increased. Many WECs are planned for deployment close to shore where tidal changes are most outspoken, thereby inducing a design challenge for such a system.

An important advantage of the selected systems, is the relatively simple line configurations. In several other studies, mooring configurations with risers and sinkers are proposed, but as illustrated in previous failures in the O&G sector, most failure of lines are occurring at points on the lines, where elements are attached.

All the systems had the great advantage of being disconnectable, meaning that the mooring can be installed separately, while the WEC is towed to the site and hooked-up to the mooring. This forms a great advantage in installation, maintenance and decommissioning. The very light systems induce an advantage in the easier installation and a requirement of smaller vessels and installation equipment, while the synthetic lines also induce an improved tension fatigue compared to e.g steel. The synthetic lines are more vulnerable to damage, but the technology has improved, and protective jackets, connection types etc. drives the use of synthetic ropes forward. One very beneficial outcome of the

use of the selected mooring systems is the reduced mooring loads and the highly reduced seabed footprint compared to traditional catenary system. In the developed systems, the required space is much less and forms a significantly lower influence on the seabed.

A topic, which has only been considered briefly in the MSLWEC project, is the umbilical. The systems require different approaches for the handling of the umbilical and this might form important drawbacks and advantages between the different system, considering layout and cost. This should be a topic of future analysis.

## Task 6.3: Evaluation of Need for Further Research and Development

The MSLWEC project analysed, designed and optimized mooring systems for large floating WECs and provided knowledge on several topics, thereby highlighting the need for further improvement and research into a number of topics.

As presented in the previous chapters, the hydrodynamic modelling still forms an area of investigation. This is particularly present for overtopping devices, where the use of linear theory, which has been seen in most design cases, induces significant errors. The use of CFD to calibrate the model was initiated in the MSLWEC project and presently needs further work and implementation.

Since the MSLWEC project primarily considered survivability in extreme cases, future development of the mooring solutions should consider more detailed analysis of fatigue and accidental limit states. In relation, the umbilical design should be treated more careful and in a more direct relation to mooring design. In order to get a complete description and design of a final solution, the analysis and development should treat all mooring components (like connections) more detailed.

The cost analysis in the project illustrated a significant change of cost as consequence of improved experience. Through actual deployments of systems, more experience is gained and cost estimations should improve significantly. The project identified cost drivers in each mooring system, but this topic can be extended as more experience is gained. Naturally, cost tends to vary in time, particularly insurance cost is affected by the experience, and updating and further detailing the mooring cost database is, therefore, an area of continuing work.

The work and cost estimations illustrated a need for further development of anchors in particularly SALM systems where a single anchor needs to provide all strength. The MSLWEC project considered gravity based solutions, but required an unrealistically large component. Future research should aim at finding more effective solutions.

Finally, the MLSWEC project has provided great knowledge on mooring design and application of synthetic materials on large WECs. The great potential of these solutions are obvious to consider for other applications and reduce cost for other offshore structures. The continuing development and knowledge is greatly dependent on experience in the topic and actual deployments of the systems.

# WP7: Dissemination and Project Management

The work of the MSLWEC project was disseminated thoroughly during the project period and has been presented at several seminars at the Danish Partnership for Wave Power, the Wave Energy Industry Business2Business events and at MSLWEC workshops.

During the project runtime, the work and outcome has been disseminated in 22 publications including:

- 3 papers in scientific journals.
- 6 presentations at international conferences with papers published in conference proceedings.
- 12 technical reports.
- 1 Ph.D. Thesis.

While most papers are directly related to the MSLWEC work and presented in the previous chapters, the two publications [21, 22] are not directly related to the project but include findings from the work. All publications are listed in the References.

# Conclusions and Summary

The present report has described the work conducted in the MSLWEC project since it started in June 2014 and ended in June 2018. The work has been aimed at improving mooring design for large floating WECs in order to improve reliability and secure a high level of cost-efficiency. The project has provided understanding of methodologies and tools used in mooring design and provided approaches to use in initial designs. The project illustrated the great potential of using light and compliant synthetic ropes, and particular the novel solution of using nylon. Work has been aimed at both experimental and numerical approaches and has provided a comprehensive description of the applicability of an optimization routine to find safe, low-cost mooring solutions. The work illustrated a great potential for LCoE reduction as a result of both improved layouts, but also the gained experience on cost estimation during the project. The main advantage of the mooring solutions found for the four partner WECs, is the improved reliability, which both ensures low cost but also survivability throughout the planned lifetime.

Prior to the project kick-off, a number of milestones and commercial milestone were defined. The project managed to reach all these as described in the tables at the following pages.

## Commercial Milestones

| # | **Milestone Description** | **Work Description** | **Ref.** |
|---|---|---|---|
| CM1 | Report on design and cost of current mooring solutions of partner WECs | An investigation described the initial mooring layouts for the partner WECs and estimated the initial mooring cost at the project initiation. | [2] |
| CM2 | Report on impact of cost of selected mooring solutions on CoE of partner WECs | The LCoE for the partner WECs were estimated based on the initial mooring solutions. Afterwards, the cost was evaluated using the final solutions found in the optimization and with inclusion of improved cost knowledge. The data was compared, and illustrated significant reduction. | [15] |
| CM3 | Report on potential cost reduction through large scale production | The cost of the final mooring solutions was assessed in order to evaluate the influence from large scale production. A great potential for future cost reduction was highlighted as consequence of mass production and farm installation. | [16] |

## Milestones

| # | **Milestone Description** | **Work Description** | **Ref.** |
|---|---|---|---|
| M1 | Acquisition of selected numerical tools | A comprehensive assessment and comparison of numerical tools were performed and the commercial software package OrcaFlex was selected. | [3, 4] |
| M2 | Hiring of Ph.D. candidate | Completed prior to project kick-off. | - |
| M3 | Report on mooring solutions for preliminary analysis | A number of potential mooring solution candidates were selected based on the initial mooring layouts for the partner WECs. | [2] |
| M4 | Report on results of preliminary analysis including selection of final candidates | A preliminary quasi-static analysis was used to design the mooring solution candidates for each of the partner WECs. Based on the outcome and requirements from developers, a final candidate was selected for each. | [8] |
| M5 | Report on validation/calibration of analysis tool | A test campaign was used to generate data for use in the validation of numerical tools. | [7, 9] |
| M6 | Report on full dynamic analysis | A full dynamic analysis was utilized in an optimization routine in order to design and investigate the mooring solutions for each partner WEC. | [14] |
| M7 | Summary of findings and project | The present report. | [20] |

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