Open Sea Operating Experience to Reduce Wave Energy Costs

Deliverable D2.4

Recommendations for WEC mooring guidelines and standards

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EXECUTIVE SUMMARY

This document represents Deliverable 2.4 (D2.4) of the OPERA Work Package 2 (WP2). The key objective of WP2 is to de-risk two mooring innovations, namely, the Karratu shared mooring system and the elastometric Exeter Tether, through a combination of comprehensive numerical modelling, an open sea demonstration programme and a dedicated component bench testing programme. A description of the contributions of this deliverable is as follows:

D2.4 Report: Recommendations for WEC mooring guidelines and standards. (Month 40). Report on the assessment of gaps in knowledge based on findings from open-sea demonstrations to inform about possible additional requirements towards existing or new wave energy codes or standards (to be integrated to the overall recommendations for standards from WP5/D5.2). The report is taking findings described in OPERA-WP2 deliverable D2.1, D2.2 and D2.3 and provides recommendations for the wave energy industry.

At the outset of the report, recommendations from existing standards are summarised. This is followed by a description of lessons learnt from modelling, design and condition monitoring of the system. These are used to provide suggestions for improving the recommended practice in the development of mooring systems in the marine industry.

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ABBREVIATIONS AND ACRONYMS

MRE	Marine Renewable Energy
DP	Deployment Phase
CMS	Condition Monitoring System
DMaC	Dynamic Marine Component
3-T	Tension-time-temperature
DoA	Description of Action
RPN	Risk Priority Numbers
DAQ	Data acquisition
TCLL	Thousand Cycle Load Limit
MBL	Minimum Breaking Load

1. INTRODUCTION

Real open-sea deployment experience is essential to fully understand the challenges in MRE device performance and lower the associated risks that shall lead to improved harvesting of the vast European resource and contribute to environmental and economic goals.

The main objective of the OPERA project is to collect, analyse and share open-sea operating data and experience to validate and de-risk industrial innovations for wave energy, taking them from TRL3-4 to TRL5 and opening the way to long term cost-reduction.

The aim of WP2 is to de-risk innovations that lower mooring costs over 50% and enhance structural survivability. The key objective of WP2 is to de-risk two mooring innovations. This includes the Karratu shared mooring system [1] that reduces mooring line length and cost in WEC farm and the Exeter Tether [2]. The Karratu system reduces the number of mooring and anchoring components, thereby reducing costs and increasing the reliability for arrays of MRE devices.

Through a combination of comprehensive numerical studies, open sea demonstrations and a dedicated component bench testing programme, WP2 objectives are achieved through the following:

- Design, manufacture and bench-test a novel elastomeric tether
- Design, assemble and incorporate the condition monitoring systems (CMS) and the elastomeric tether in the shared mooring
- Evaluate shared mooring open-sea operation without (Phase 1) and with (Phase 2) elastomeric tether

The deliverable D2.4 is taking findings described in OPERA-WP2 deliverable D2.1, D2.2 and D2.3 and provides recommendations for the wave energy industry, and aims to address Task 2.4. The task description, as extracted from the DoA, is as follows:

T2.4 Evaluation of shared mooring configurations. (Months: 12-40) – Leader: UNEXE, Participants: TECNALIA, OCEANTEC, DNV-GL, GM, UCC

> '…the task will draw upon latest state of the art standard developments (such as IEC, DNV, EMEC) and will use the collected data from the open sea demonstrations to search for possible additional requirements not introduced to these standards that will feed into WP6.'

D2.4 draws upon the latest state of the art standard developments (such as IEC, DNV, EMEC) and research outputs from other tasks in WP2 to recommend additional requirements for the mooring line system as a key part of the OPERA project.

This deliverable combines the research outcomes from earlier deliverables in WP2 relevant to modelling, design and condition monitoring of mooring systems to identify gaps in knowledge and inform existing codes in the industry.

To investigate the influence of geometric scale on tether performance, tethers with three different diameters were produced for lab testing. Harmonic and ramp tension-tension tests were performed on these samples at Dynamic Marine Component (DMaC) that enabled a key mooring system metric, namely axial stiffness, to be quantified. Fatigue performance, as well as tether hysteresis and contraction behaviour, was also investigated.

Tests at Lankhorst Euronete provided insight into the design process which informed the two full-scale Tethers which used in the OPERA project during Deployment Phase 2 (DP2).

Also, two condition monitoring systems to facilitate continuous open sea mooring load data collection during the two deployments were designed.

A comparative study of the two deployment phases is conducted using low, medium and extreme environmental conditions with similar, but not identical, environmental conditions. The OrcaFlex simulations for Deployment Phase 1 (DP1).are validated by data collected from continuous load monitoring of the shared mooring system spanning from 13/12/2016 to 11/12/2017. A similar validation practice for DP2 utilises a shorter record of field data collected between 15/11/2018 and 28/01/2019.

Key sections of this deliverable and their contribution of this deliverable are described below.

Section 2 highlights the need for additional recommendations for mooring systems in the marine renewable energy (MRE) industry whilst describing existing guidances and recommended practices.

Section 3 describes the design process, specifications of the condition monitoring system and the numerical evaluation of the mooring system.

Finally, Section 4 provides recommendations to inform existing standards and recommended practices in the

2. AVAILABLE STANDARDS AND GUIDANCE

Emerging technologies such as wave energy often use sub-systems and components that are novel, or have known history in environments that are significant different to the application environments for emerging technologies. Wave Energy Converter (WEC) mooring systems are often exposed to different load characteristics and innovative configurations and components are considered, therefore, there is little to no relevant service history and the novel aspects of the component are not adequately addressed by existing guidance's.

Therefore, technology assessment must be performed to evaluate component behaviour by following a structured certification methodology. The assessment can be conducted at the necessary level of system hierarchy to separate proven technology from novel technology by using the technology matrix presented by DNVGL-SE-0163 [3]. The matrix combines elements including 'knowledge of technology status' and the 'application area'. The combination are categorised in different classes ranging from Class 1, representing known technology applied in an known environment; towards Class 4, where novel technologies are used in an unknown environment that results in significant technical uncertainties.

The Technical Committee on marine energy of the International Electrotechnical Commission (IEC/TC114) is currently developing Technical Specifications (IEC/TS), several of which have been approved and are in different status of preparation. OPERA will provide the first documented application of several IEC/TS to a real-case wave energy device. This is a crucial step in improving and ensuring the practical applicability of IEC/TS and towards the establishment of standards in the sector.

IEC/TS62600-10 an 'Assessment of mooring system for marine energy converters' (approved in March 2015) will focus on the uncertainties and associated risks in mooring designs for marine energy converter, with a focus towards technical challenges as a result of highly coupled dynamic system, and application of novel mooring components and configurations. Aiming to enhance knowledge and de-risk design processes and also in aiding in the cost reduction of the mooring system, reduction in uncertainties can be achieved through demonstration experience from realistic sea trials. Sea demonstrations will generate essential data and knowledge that can be used to establish recommendations providing the basis for aiding in the standard development.

While there are view dedicated marine renewable energy (MRE) standards, specific MRE standards encompassing mooring designs are further limited. Various classification societies have developed individual standards that provide existing guidance to the industry. This includes:

- IEC TS 62600-10 (moorings)
- DNV-OS
    - DNV-OS-E301 - Position Mooring - Rules and standards [4]

    - DNV-OS-E302 - Offshore Mooring chain [5]
    - DNV-OS-E303 - Offshore Mooring Fibre Ropes [6]
    - DNV-OS-E304 - Offshore Mooring Steel Wire Ropes [7]
    - DNV-OS-E304 - Design, testing and analysis of offshore fibre ropes [8]
- DNV-OS-J103 - Design of Floating Wind Turbine Structures [9]
- DNVGL-ST
    - DNVGL-ST-0119 - Floating wind turbine structures [10]
    - DNVGL-ST-0164 – Tidal turbines [11]
- DNVGL-SE
    - DNVGL-SE-0422 - Certification of floating wind turbines [12]
    - DNVGL-SE-0163 - Certification of tidal turbines and arrays [3]
- ClassNK - Guidelines for Offshore Floating Wind Turbine Structures [13]
- ABS code - Guide for Building and Classing Floating Offshore Wind Turbine Installations [14]

Furthermore, Part 7 of ISO 19901 [15] provides standards for station keeping systems in floating offshore structures and mobile offshore units utilised in the oil and gas sector. These recommendations can be translated for use in the renewable sector.

The standards listed above draw from existing standards in the materials technology, structural design or mooring systems industries. Stakeholders involved in the design, deployment, certification and condition monitoring of MRE mooring systems should demonstrate that the process have been undertaken is in accordance with these internationally recognised standards or guidelines, but often the uncertainties in novel MRE designs will not allow this.

OPERA has its objective to provide first open sea operating data to inform specific standards for wave energy applications, including structure performance including mooring and electrical equipment. The new knowledge due to open sea demonstration will permit the application of IEC TS 62600-10 (moorings) and contribution to improve offshore rules/technology qualification process towards wave energy converters. The findings will also inform the OPERA deliverable D5.1 (section 2), 'Wave Energy Measurement Methodologies for IEC Technical Specifications', where the application of the TS are evaluated and investigated so that these results can provide recommendations and feedback to the IEC TS.

To date the established mooring standards are typically developed for mooring applications relevant for the offshore oil and gas sector, where specific emphasis has been given to various aspects within the designs.

DNV-OS-E301 [4] informs general material testing and other requirements for position moorings. Since the Exeter Tether is a fibre rope, relevant guidance from this standard suggests that the rope should not be in contact with the sea bed or exposed to direct sunlight and its entire length should be submerged at all times during service. Ropes are intended to work in deflection, and tethers are not. Thus, a rope that tolerates working under deflection may not need an external jacket. Further information on types of rope is provided in DNVGL-OS-E305 [8].

DNV-OS-E301 also provides information about the stud chain, shackles, buoys, steel wire ropes, fibre ropes, fairleads and anchors. It suggests that environmental effects shall be taken into account, as appropriate for the location of the mooring. These include waves, wind, current, marine growth, tide and storm surge, earthquake, temperature, snow and ice.

The environmental effects to be applied in mooring line response shall include the most unfavourable combination of wind, wave and current with a return period of no less than 100 years for the combination which creates higher mooring loads. The environment aspects such as intensities and direction shall also be considered in the assessment. In the condition of lack of information regarding the environment condition, the assessor should decide on a set of the most conservative environmental conditions.

It is noted that the absence of a minor effect may sometimes lead to higher line tensions than a moderate intensity of that effect; e.g. through a reduction in damping of platform motions. The characteristic load effects are obtained for stationary, environmental states. Each stationary environmental state may be specified in terms of available wind, wave and current parameters.

For wind, these include mean wind speed over a 1 hour averaging period 10 m above sea level (U1 hour, 10 m), wind spectrum function, wind direction and a mean wind speed 10 m above the water surface with a 100-year return period should also be used.

For wave these include significant wave height, peak wave period, wave spectrum (JONSWAP or double-peaked) with return periods of 100 years, wave energy spreading function (long crested waves or a cosine to the power of 4) and main wave direction.

Finally, for the current profile, surface current speed, current profile over depth and current direction must be used in conjunction with a surface current speed with a 10-year return period.

It is important to perform calculations for several sea states along the 100-year contour line to make sure that the mooring system is properly designed. If it is not possible to develop a contour line due to limited environmental data for a location a sensitivity analysis with respect to the peak period for the 100 year sea state should be carried out.

WP2 of the OPERA project presents a comparison of the differences in the motion of the buoy and loads experienced at the shared Karratu mooring system when a conventional fibre (polyester) rope and the novel Exeter Tether are incorporated in Deployment Phase (DP) 1 and DP 2, respectively.

As DNVGL-OS-E303 [6] specifies quality targets for design, manufacturing, handling and service for both offshore fibre ropes and tethers in taut, semi-taut and catenary mooring systems, the learnings of this research can be used to support existing recommendations and inform additional recommendations to this offshore standard. This standard differentiates between an offshore fibre rope and tether. The former is composed of a braided or helical strand construction that accommodates deflection under tension, whereas, the latter is composed of a load-bearing core of parallel elements with a jacket holding the bundle of load-bearing elements together.

DNVGL-OS-E303 [6] suggests that the Tension-time-temperature (3-T) performance characteristics [8] of the chosen yarn must be based on the designated service. It postulates that long-term and mobile mooring systems should be operated with sufficient margins against failure [4], abrasion resistance and low variability in change-in-length characteristics. Investigation of a subset of the following parameters is recommended for characterisation of the expected performance of a fibre-rope or fibre-tether segment in mobile or long-term mooring with the number of test specimens listed in Section 3.2 of [6]:

- 3-T performance characteristics
- Cyclic endurance
- Splice integrity
- Change-in-length characteristics
- Torque and twist characteristics
- Breaking strength
- Resistance to soil ingress
- Hysteresis heating
- Low-tension durability

Ideally, test specimens should be produced and tested before production of the final component. It is also recommended that one set of the termination hardware should be tested in conjunction with the fibre line during break testing and cyclic endurance testing.

It is expected that the condition of offshore fibre ropes and tethers is managed during service, in order to ensure sufficient margin towards relevant failure modes based on a Condition Management Program.

Stress rupture is identified as a failure mode for polyester and Exeter Tether, therefore, tension measurements can provide vital input for the assessment of accumulated damage. If measured or suspected tension level exceeds 70% mean breaking load (MBL) for a fibre line during service lifetime, it should be taken out of service and re-certified or discarded [6].

3. RESEARCH OUTPUTS FROM OTHER DELIVERABLES

D2.4 outlines the design and improvement of the mooring lines used in the project. The Exeter Tether prototype was developed by the University of Exeter in conjunction with manufacturers Ley Rubber and Lankhorst Euronete. The use of the tether is based on detailed performance and durability testing including bench test data of multiple tether samples.

This section summarises learnings from previous deliverables in WP2. Details of these can be accessed in the following documents:

- D2.1 Mooring load and response monitoring system design
- D2.2 Mooring open-sea operating data analysis
- D2.3 Elastomeric tether performance and durability

3.1 TETHER DESIGN AND MANUFACTURING

The innovative mooring systems underwent thorough bench testing at different facility including the Dynamic Marine Component (DMaC) test facility, aiding in the certification processes and de-risking prior to deployment in the open sea. The DMaC test facility was used to investigate performance and durability metrics of three different Exeter Tether scale prototypes (three samples of each size). Additional tests were carried out at rope manufacturer Lankhorst Euronete to determine the minimum break load of a full-scale tether sample, including break tests.

3.1.1 SMALL- AND FULL-SCALE PERFORMANCE TESTS

IN ORDER TO INVESTIGATE THE INFLUENCE OF GEOMETRIC SCALE ON TETHER PERFORMANCE, TETHERS WITH THREE DIFFERENT DIAMETERS WERE PRODUCED, WITH ALL SAMPLES EXCEPT P4BC MANUFACTURED WITH AN EYE-TO-EYE LENGTH OF 5M.

Table 1 lists the specifications of each sample which were designed. It can be noted that three identical samples were manufactured for the P2 and P3 sizes. For the P4 series, P4A and P4B were identical.

Testing of the 9x short Exeter Tether samples (P2, P3 and P4 series) took place during early February (Month 13) at Dynamic Marine Component (DMaC) test facility, Penryn Campus (University of Exeter), with one additional test carried out on a full-scale (P4) sample at Lankhorst Euronete, Maia (Portugal), during early March (Month 14).

a. b.

FIGURE 1 DIFFERENT LOAD CARRIER AND JACKET CONSTRUCTIONS USED FOR SAMPLES: A) P4A/P4B AND B) P4C.

TABLE 1: SAMPLE SPECIFICATIONS

Designation	Outside diameter (mm)	Core diameter (mm)	Construction	Estimated MBL (kN)[1]
P2A	93.0	25.0	PET load carrier: 3 x 6 x 2000	222.0
P2B				
P2C				
P3A	130.0	35.0	PET load carrier: 3 x 6 x 2000	435.0
P3B				
P3C				
P4A	232.4	60.0	PET load carrier: 3 x 6 x 2000 PA jacket: 3 x 7 x 1680	1303.0
P4B				
P4C			PET load carrier: 11 x 6 x 2000 PA jacket: 3 x 24 x 1680	

[1] Estimate based on measured yarn breaking strength, design linear density and realisation factor.

FIGURE 2: P2 AND P3 SERIES SAMPLES.

The majority of testing was carried out at DMaC (Figure 3a) with one load-to-failure test carried out at Lankhorst-Euronete (Figure 3b) because the expected MBL was out of the working range of DMaC. A mixture of harmonic and ramp-hold-ramp load profiles were used to quantify static and dynamic stiffness of the samples. Stepped load increase/decrease were carried out to investigate contraction/expansion of the tether cross section during loading/unloading. A Thousand Cycle Load Limit (TCLL) test was also conducted to determine fatigue performance.

The purpose of the tests was to investigate tether performance and durability using three geometric scales.

a b

FIGURE 3 : TENSION-TENSION TEST MACHINES: A) DMAC AND B) LANKHORST-EURONETE MACHINE

Performance and durability tests were carried out using the DMaC facility at UNEXE during 1st-17th February 2017. Applied tensions were measured using a 20 tonne load cell, with elongation of the working length of the sample measured using an Optitrack™ motion tracking system (manufactured by Natural Point Inc.). The load cell was a pancake DSCC type, manufactured by Applied Measurements, with a full-scale error of 0.097%. The load was recorded at 50 Hz and a resolution of 0.023 kg through a National Instruments cRIO 9022 and C-series module 9237. Optitrack has an error of 0.2 mm and a sample frequency of 50 fps. Several key test stages were used to determine sample performance and durability:

- Harmonic (HC): force- and displacement-controlled tests
- Constant load (HD): to investigate sample creep and relaxation
- Stepped load plateaus (SLI and SLI/D): to study diametrical changes under loading
- Fatigue testing (TCLL): using a Thousand Cycle Load Limit test programme.

Full details of the tests can be found in Deliverable 2.3 Elastomeric Tether Performance and Durability and only a summary of the findings is provided in the subsequent subsection.

Uncertainties in unknown components requires performing a detailed component FMEA to deduce cumulative Risk Priority Numbers (RPN) as seen in **¡Error! No se encuentra el origen de la referencia.**.

TABLE 2: FMEA ANALYSIS OF THE ELASTOMETRIC TETHER AND THE CMS COMPONENTS INVOLVING THE DESIGNATION OF APPROPRIATE RPN VALUES WHILST HIGHLIGHTING FAILURE MODES.

Component	RPN	Failure mode
ELASTOMETRIC TETHER		
Tether	142	Compression Failure; Fatigue; Termination failure
MONITORING SYSTEM		
Node load pins	102	Cable failure; Fatigue; kinking
Load shackles	98	Fatigue; Corrosion
Data Acquisition system	18	Loss of Power

3.1.2 TETHER MANUFACTURE AND BENCH-TEST DEPLOYMENT

Following testing of all of the samples at DMaC and after discussion with Lankhorst, variant P4C was designed with a different construction and manufactured during February 2017. This sample had longer splices than the other 8 samples and as such had an eye-to-eye length of approximately 7.5m. It is this construction which was used for the tethers deployed at BiMEP. Referring to Figure 1a and Figure 1b the differences between P4A/P4B and P4C are clear. The earlier P4 series prototypes comprise strands twisted into small subropes resulting in a very open braid (Figure 1a). The possibility of particulate/biofouling ingress as well as a relatively low overall breaking strength due to the high degree of yarn twist led to the specification of 3 yarns laid parallel in a tighter, flatter braid (Figure 1b). The braid angle of the P4C variant is also steeper and hence closer to what was originally specified.

The load-to-failure test carried out at Lankhorst Euronete (sample: P4C) was used to confirm the break load of the tether, albeit based on one sample. The measured MBL was 1597.5 kN, almost 23% higher than the predicted failure load.

The final manufacture of 2x 70m tethers took place at the Lankhorst's Maia, Portugal Factory (Figure 4a); and was delivered to Bilbao in June 2017 (Figure 4b). The deployment of the tether for DP2 took place in August 2018 (Figure 4c).

a

b

c

FIGURE 4: TETHER MANUFACTURE AND DEPLOYMENT: A) MANUFACTURE AT LANKHORST EURONETE, B) DELIVERY TO BILBOA AND C) DEPLOYMENT AT BILBOA

In order to confirm that the size is appropriate for the second MARMOK-A5 deployment, 3x3 short versions of the tether were manufactured during December 2016 at Lankhorst Euronete's production facility in Maia, Portugal. A general schematic of the tether is shown in Figure 5.

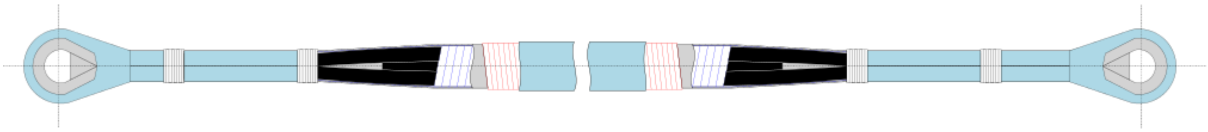


FIGURE 5: SCHEMATIC OF THE EXETER TETHER SHOWING LOAD CARRIER (LIGHT BLUE), ELASTOMETER CORE (BLACK), ANTI-FRICTION LAYER (WHITE/BLUE) AND PARTICULATE FILTER LAYER (WHITE/RED).

3.1.3 KEY FINDINGS

- Performance testing using harmonic displacement- and force-controlled tension-tension tests were used to quantify axial stiffness for three different Exeter Tether scale prototypes. The axial stiffness of samples is highly dependent on previous loading, to a much greater degree than conventional synthetic ropes.
- A Thousand Cycle Load Limit test was carried out on the smallest prototype size (estimated MBL = 222kN) and failure occurred after 1087 cycles (1000 cycles at 1-50%MBL and 87 cycles at 1-60%MBL).
- Inspection of the failed sample suggests that failure occurred in proximity to the end of the elastomeric cores. Minor design changes, including providing a chamfer on the end of the exposed cores and modification of the layer topology have since been implemented to mitigate the risk of this occurring in service.
- A full-scale (in terms of diameter) sample was pulled until failure and achieved a break load of 1597.5kN (or 162.9 Tonnes), which is almost 23% higher than the predicted failure load. This is encouraging for the second OPERA deployment as it provides a suitable Factor of Safety based on numerical simulations of the MARMOK-A5 device and Karratu mooring system.
- Deconstruction of the failed sample has highlighted several potential design improvements that will be included in the final OPERA design.
- Assessment of elastomeric mooring component (novel component) at small scale and full scale informed about the important in behavior and durability. The steps implemented helped to inform the certification processes, reduced risk and enabled to decide on final design parameters.

3.2 CONDITION MONITORING FOR CERTIFICATION PURPOSES

Two mooring Condition Monitoring Systems (CMS) were designed and manufactured during the OPERA Project. This was the result of an extreme event at the end of DP 1 resulting in the catastrophic failure of the CMS system. The loads exceeded the maximum CMS design loads, which were chosen on based on sacrificial design criteria, in order not to compromise the MARMOK device itself and its mooring system.

3.2.1 CMS DESIGN

The CSM design for DP 1 included 4x 55t Load Shackle where the cables were routed back from Node 1 and Node 4 to the MARMOK hull. A Wire Rope 'Cradle' system was used to support the Load Shackle Cable run back to the MARMOK. At the MARMOK hull, a J-Tube was used to route the Load Shackle Cables up the outside of the WEC to a Junction Box (Figure 6). From the Junction Box, one common cable will take the signal from all four Load Shackles back to the DAQ system.

Full details of the CMS design can be found in Deliverable 2.1 Mooring load and response monitoring system design and only a summary of the findings is provided here.

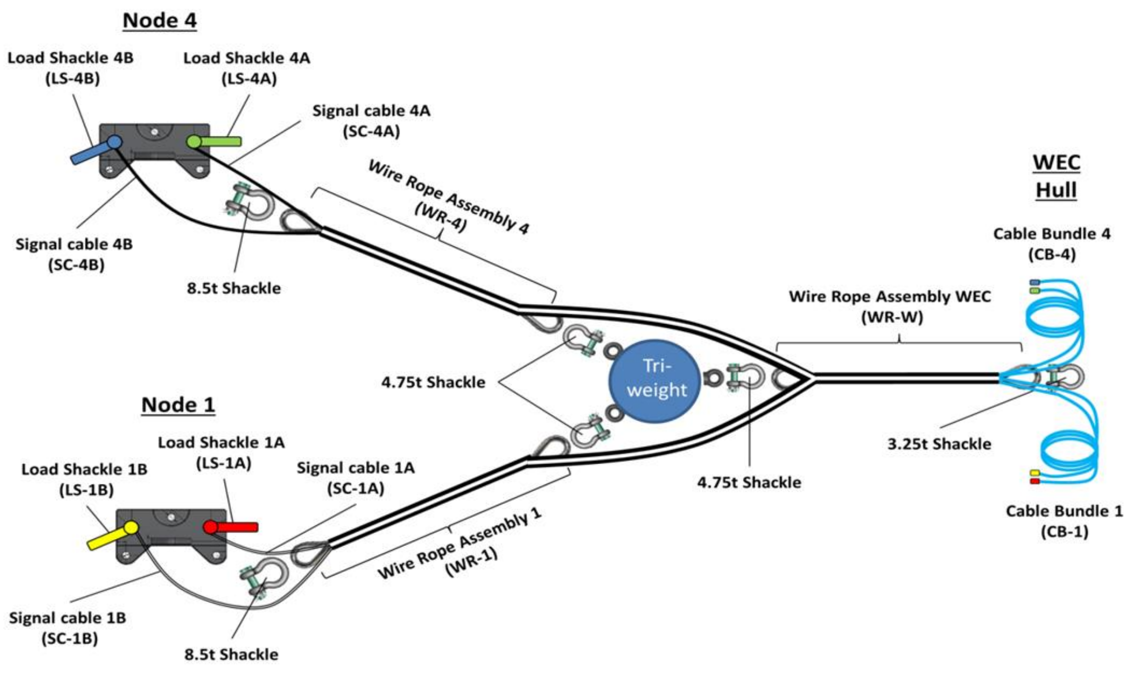


FIGURE 6: SCHEMATIC OF THE CMS DP1 WITH MAIN COMPONENT LABELS (NOT TO SCALE).

The re-designed system (DP 2) comprised of two armoured cables which run directly from Node 1 and Node 4 to the junction box on MARMOK via the J-tubes (Figure 7). The Load Shackles were re-calibrated and used again as well as the DAQ system. The bottom of the J-tubes has been modified to include composite bell mouths in order to reduce bending stresses and abrasion during use (Figure 8).

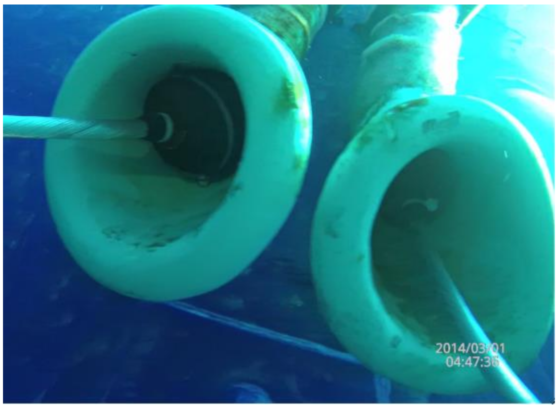


FIGURE 7: RE-DESIGN OF J-TUBE (DP2) TO REDUCE STRESS TO CABLING SYSTEM.

Unlike the first design, which had separate steel wire cables and a Tri-weight, the new design utilises the cable's armouring strands to support the hanging catenary. Aramid cable grips are used to transfer loads from the armouring to the Node and MARMOK attachment points.

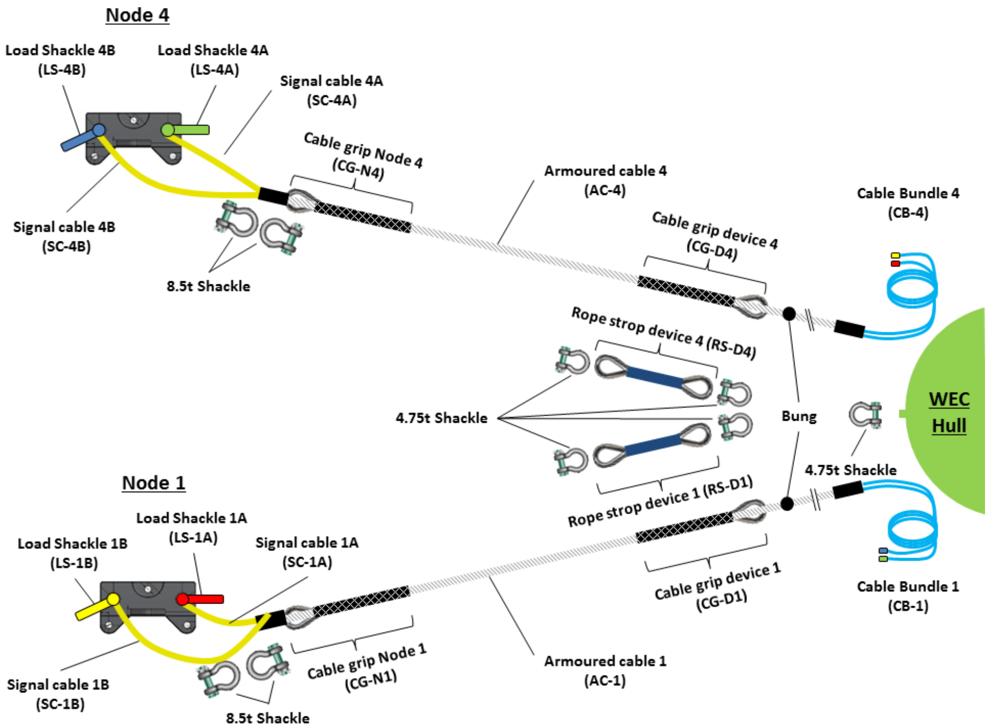


FIGURE 8: SCHEMATIC OF THE CMS DP2 WITH MAIN COMPONENT LABELS (NOT TO SCALE).

A 55t Green Pin® (Figure 9) standard bow shackle with safety bolt is specified for the load shackle design. The pins supplied with the shackles are to be replaced with load pins, manufactured from 17-4PH H1075 Stainless Steel to match the specific dimensions of each shackle. The use of this steel maintains the specified Safety Factor of 6 on the Green Pin® shackle specification. Given the working load limit of 55t this equates to a minimum breaking load of 330t.

FIGURE 9: ONE OF 4X 55T LOAD SHACKLE PRIOR DEPLOYMENT

3.2.2 POST-INSTALLATION EXPECTION

For DP 1, the CMS was installed in December 2017 followed by the extension of Celda wire cable F1-B1 and F2-B2 on 08/12/2016. The mooring data register started on 13/12/2016 and ended on 11/12/2017 providing achieving the target data collection period.

However, due to a heavy storm, mooring load cell data loss was experienced at the F1 catenary line on 13/01/2017. A gradual deterioration of the remaining Cadena signal continued during 2017 until complete loss of all signals on 11/12/2017.

Various wear and corrosion issues were identified after Phase 1 (Figure 10), which were recorded for further recommendation. This includes the failure of the CMS wire rope, Celda line in DP 1 and shackle failure. However, the cable strain relief brackets were observed to be intact.

Additionally, considerable marine growth was observed on the mooring system which is expected to have implications for the OrcaFlex numerical model set up for validation.

For DP 2, the load shackles were maintained and re-calibrated, and the CMS was installed again on 11/2018. The mooring data register logged information from 15/11/2018 to 28/01/2019 for DP 2, generating sufficient data enabling comparison between DP 1 and DP 2.

At time of report preparation the CMS for DP 2 was not recovered and detailed learnings were not obtained. As a consequence recommendation on CSM designs for MRE devices to inform standard development can only be based on experience gained from DP 1.

a b c

FIGURE 10: WEAR AND CORROSION ISSUES OBSERVED DURING DP1, A) MARINE FOULING ON LOAD SHACKLE, B) ROTATION PIN FAILURE ON LOAD SHACKLE, C) FOULING AND CORROSION ON SUBSEA CONNECTOR

3.2.3 KEY FINDINGS

- Peak load calculation for CMS requires fully dynamic cable simulation: using appropriate environmental parameters and informing design load cases for the condition monitoring system;
- Introduction of sacrificial CMS load design limits are essential to protect main station keeping system and WEC device; sacrificial CMS weak points should applied;
- Load shackles were found the optimum choice, maintaining the load path of the existing mooring infrastructure and allowing a direct replacement without the need for a safety line;
- Due to identified design conflicts, it was considered necessary to locate the load monitoring shackles at the mooring system nodes as opposed to the WEC hull; the associated cable route back to the DAQ from the nodes is challenging and various options are considered;
- Full system specification of load monitoring equipment is essential to inform user and deployment contractor; including selected cable routes with support system, J-tube design and signal system;
- The signal output from the load shackles and the data logging requirements for the system needs to be carefully considered;
- Detailed deployment options are needed to be discussed ahead of deployment with the selected offshore operations contractor;
- Specific consideration needs to be given to Load Shackle pin rotation to avoid measurement errors;
- J-tube design needs to be carefully considered to avoid stress on cable system;

- Corrosion and wear characteristics are undesirable criteria, contributing significantly to accuracy and reliable signal monitoring issues;
- Load shackle location should be carefully considered and if possible to be chosen closest to the WEC device in order to avoid long distance monitoring cable designs.

3.3 EVALUATION OF SHARED MOORING SYSTEM

Validation and comparison of both deployment phases was conducted using mooring data collected at the offshore side on MARMOK device during DP 1 (without elastomeric tether) and DP 2 (with elastomeric tether) over a period from 13/12/2016 to 11/12/2017 and 15/11/2018 and 28/01/2019, respectively. The OrcaFlex simulations for DP 1 are validated from data collected from continuous load monitoring of the shared mooring system during DP 1. A similar validation practice for DP2 utilises the shorter record of field data was conducted.

Figure 1 details the Karratu mooring system specified for OPERA project. The number and name convention of the mooring components is detailed for reference throughout this document. Cell lines are numbered A (Node 1 – 2); B (Node 2-3); C (Node 4-5); D (Node 4-2). The end convention for all lines is specified by the end nearest the WEC as End A and the end nearest the anchor as End B. The cell lines end convention is specified going anti-clockwise from End A to End B for all cell lines.

All cell lines and nodes are modelled in OrcaFlex based on the design shown in Figure 1. The use of Exeter Tether is applied in the model instead of catenary polyester rope number 1 and 4 for DP2. Another difference between the numerical model of DP2 relative to DP1 is the position of umbilical line. In the first deployment, the umbilical is placed between catenary line 2 and 3, whereas in the second deployment it is between lines 1 and 4.

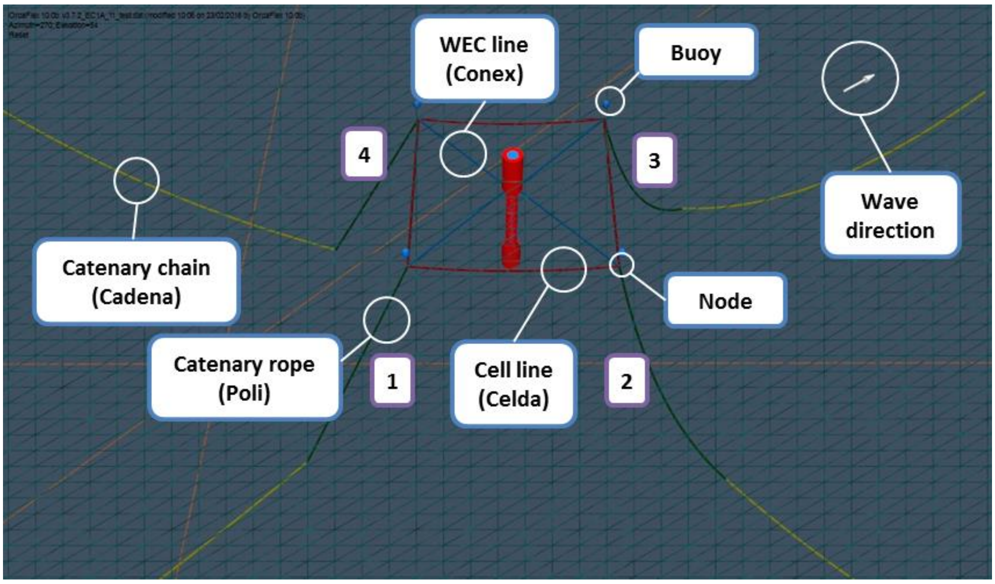


FIGURE 11: MOORING SYSTEM DEFINITIONS

Full details of the analysis can be found in Deliverable 2.2 Mooring open-sea operating data analysis and only a summary of the findings is provided here.

The two deployment phases, DP 1 and DP 2, were initially independently analysed and secondly results were compared for similar environmental conditions.

3.3.1 CONVERGENCE AND ROBUSTNESS TESTS

The original model received from Oceantec as Orcaflex model *v3.7.2_EC1A_11.dat*, was modified to remove undue complexity. A benchmark test was done to demonstrate that the results of the modified models did not change markedly from the original model. While the modified model demonstrated the same peak tension as the original model, it was surprising that variation was observed by the removal of the Nodo (3D buoy element), that were used to connect the catenary line elements.

A broad range of sensitivity and test cases for the WEC device, moored using the mooring arrangement in the preliminary deployment phase (DP 1) were conducted. The observations for start time, simulation length, number of wavelets, Cd and Ca values, number of seeds, time-step and element density summarised below:

- Start Time and Duration Sensitivity – It had been presumed that peak mooring line tensions would be associated with peak wave (crest) events, and hence convergence would be demonstrated as the simulation is commenced progressively earlier in time. However, for the candidate seastate and crest event, convergence was not demonstrated even for simulation starts up to 1600sec prior to the crest event. To address this, longer simulations of 10,800 s were performed. Although each simulation had a peak crest event at 3,742sec, none of them demonstrated largest peak tension events near this time and the predicted peak tensions were much larger than those occurring around the peak wave crest.
- Number of wavelets sensitivity - These tests were not conclusive, because the time and magnitude of the crest event is dependent upon the number of frequencies (wavelets) used to model the irregular sea. However, this investigation did illustrate the fact that larger crest events can occur by varying the number of wavelets.
- Cd and Ca sensitivity – These tests that were done demonstrated a monotonic nature variation in peak tensions due to individually adjusting the Cd and Ca values per body; except for the MARMOK Cd_axial.
- 20 Seed Analysis – This investigation demonstrated the method of evaluating a design tension from 20 independent short duration analyses. However, the application also demonstrated that the range on peak tension is very large (861kN), which indicates sensitivity to the response. Again, the correlation between peak wave crest and peak tension was observed to be poor.

- Time step sensitivity – These tests did not show convergence of the peak tension event (point in time and magnitude) with smaller time step. The point in time when the peak event occurred is disproportionately sensitive to the to the time step used.
- Element density sensitivity - These tests did not show convergence of the peak tension event (point in time and magnitude) with increased element density.

Further details regarding these texts may be found in deliverable D2.2 and *Technical Note_WP2_GM_102_v1*.

3.3.2 MODEL VALIDATION

After conducting the convergence and robustness analysis, basic responses of the moored WEC were simulated and an investigation into the divergence of response from measured data was conducted.

The comparisons between field data and simulations are completed for DP 1, which have been focused on a medium-sized storm which occurred in June 2017 and also a calm period in May 2017. The latter comparison has been applied to investigate mean position of MARMOK and pre-tensions using recommendations from existing standards. Initial large discrepancies between the measured and simulated positions (Figure 12a) have been investigated in detail and improvements suggested in the simulation model.

Incorporating advanced modifications (not stated as essential elements in standards), a fully dynamic mooring simulation was then implemented. Comparison of measurement data to simulation based on the advanced simulation (Figure 12b) highlights that significant uncertainties have been identified in case the simulation is solely based on standard approach.

The validation process has focussed on the following parameters:

- Easting and Northing of the radar antenna (Figure 13a,b)
- Heave at the CoG (Figure 13c)
- Roll and Pitch of the MARMOK (Figure 13d,e)
- Tension at the upper end of the catenary of Line #1 (Figure 14)

Environment: The comparison between measured and analysed motion and tensions, using the environmental parameters and the numerical model, has been improved primarily due to the inclusion of current profile from ADCP.

Easting and Northing: The measured mean Easting and Northing positions are greatly improved by inclusion of ADCP data, however there are still some differences in Easting and Northing of the MARMOK.

Roll and Pitch: The Roll motion evaluation from the analysis indicates it is almost negligible. This appears to be consistent, with the relative wave-direction (from 330deg i.e. toward 150deg) and the local axis (rotated 41deg clock-wise i.e. the plane of pitch is 131deg direction) of the MARMOK, are almost parallel.

However, it is not clear what environmental attribute generates the measured roll motion, which is nearly equal to the pitch motion.

Centre of Gravity: Shifting the COG does not significantly improve the difference in mean roll or pitch. The difference in mean roll/pitch may be due to the difference in mean heave, where the MARMOK onsite is riding higher in the water probably due to the pressure in the internal chamber.

Tension: The improvements to the model (ADCP data, permanent set, improved added mass & drag of the MARMOK) has significantly improved the comparison of tension standard deviation in Cadena 1.

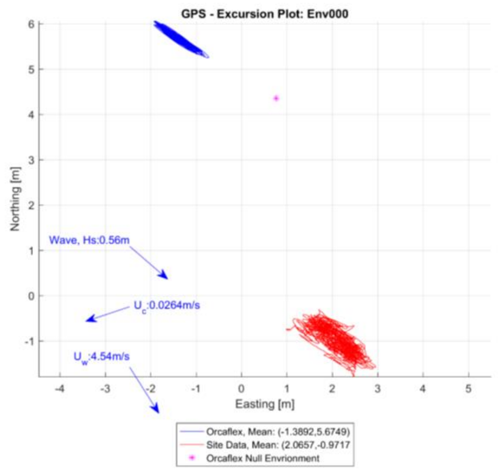
To give a best estimate of MARMOK offset the Northing and Easting motions have been “Zeroed” by removing the static (No environment) mean from the analysed, and the small environment mean offset from the measured motions, to have a common zero datum.

Although the model updates and ADCP data have improved some of the differences, there are still significant differences between measured and analysed values of:

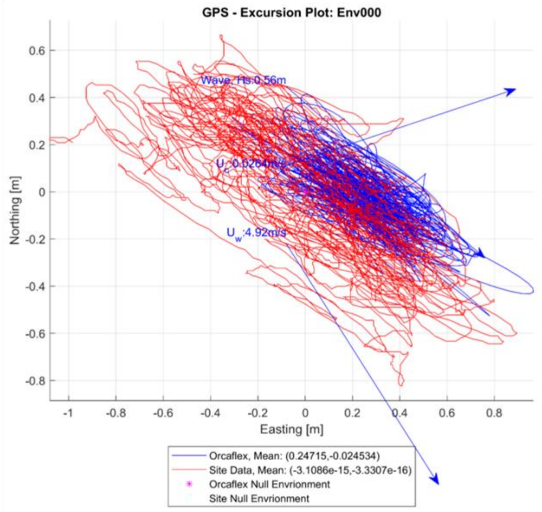
- Roll and Pitch
- Heave

A reason for these differences could be the pressure in the chamber. This may influence the mean draft of the MARMOK and consequently the roll/pitch restoring moment. This may contribute in part to the underlying difference in mean roll and pitch, however it is not enough to explain the large difference in roll motion for extreme environments. To improve the corroboration, it is recommended that the chamber pressure is considered.

It has also highlighted the need to quality check the measurement data over longer timescales than what has been considered previously. This has necessitated the creation of a local version of the database and automation of scripts.



a



b

FIGURE 12: COMPARISON OF SIMULATION RESULTS FOR HORIZONTAL MOTION A) PRIOR CALIBRATION, B) AFTER CALIBRATION

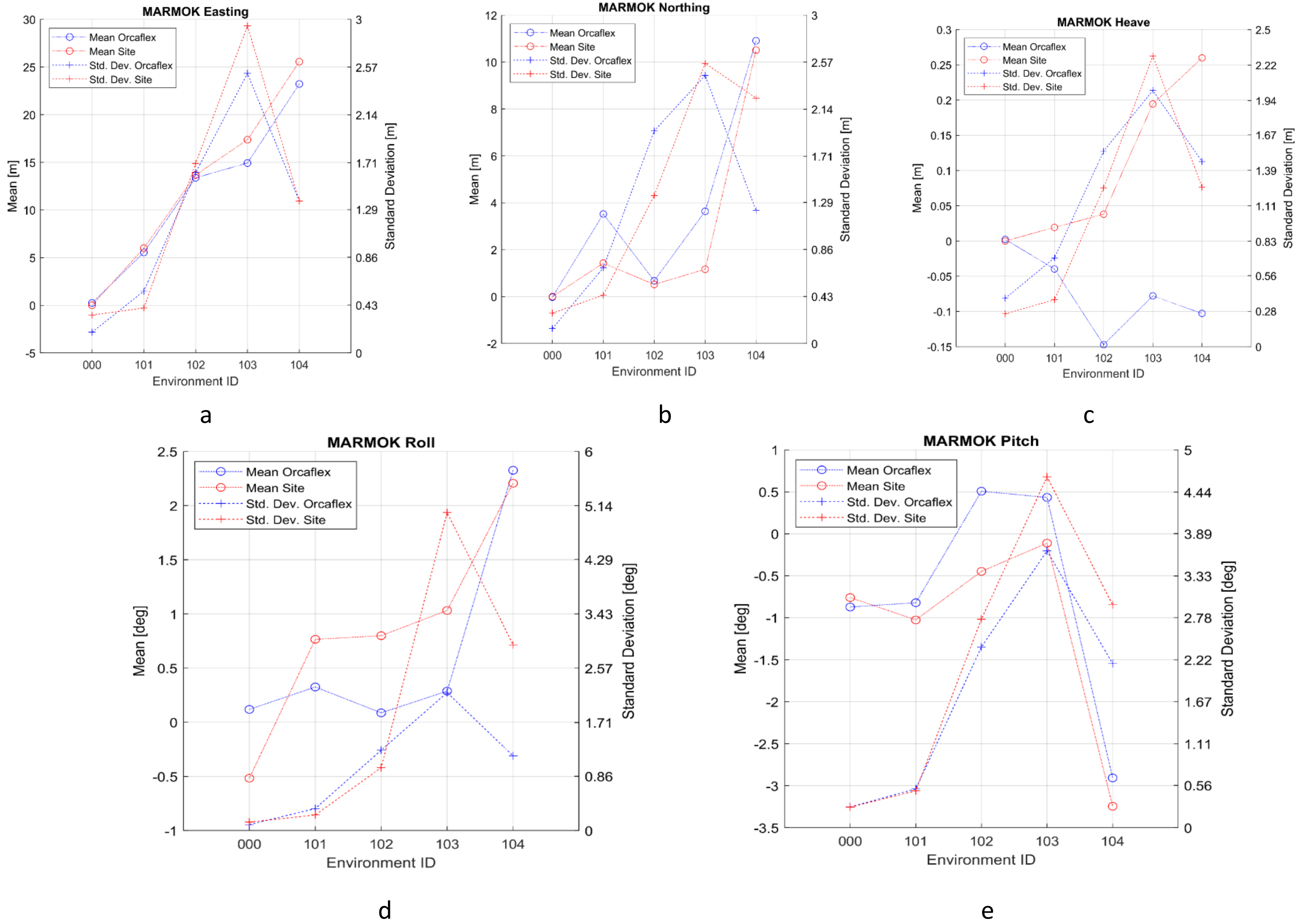


FIGURE 13: COMPARISON BETWEEN MEASURED AND SIMULATED MOTION STATISTICS FOR MARMOK A) HORIZONTAL MOTION (EASTING), B) HORIZONTAL MOTION(NORTHING), C) HEAVE, D) ROLL AND F) PITCH

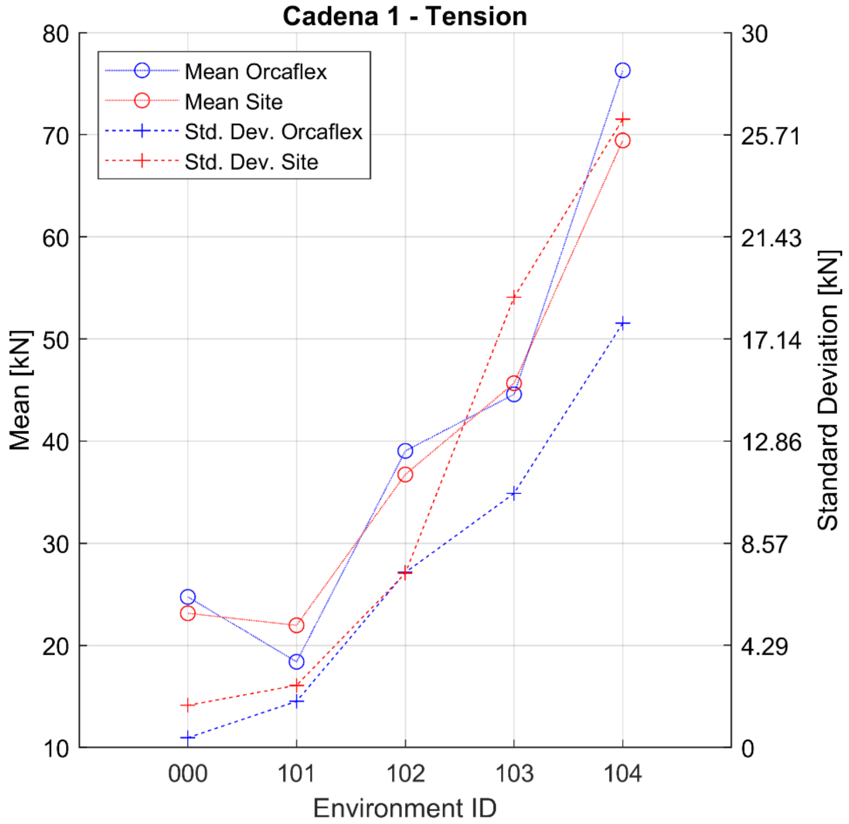


FIGURE 14: CADENA 1 TENSION – MEAN AND STANDARD DEVIATION – DP1

3.3.3 COMPARATIVE ANALYSIS OF DP 1 AND DP 2

The environmental conditions that occurred during DP 1 and DP 2 were at no time the same during the measurement campaign, and hence only similar conditions were identified for a low, medium and extreme sea condition.

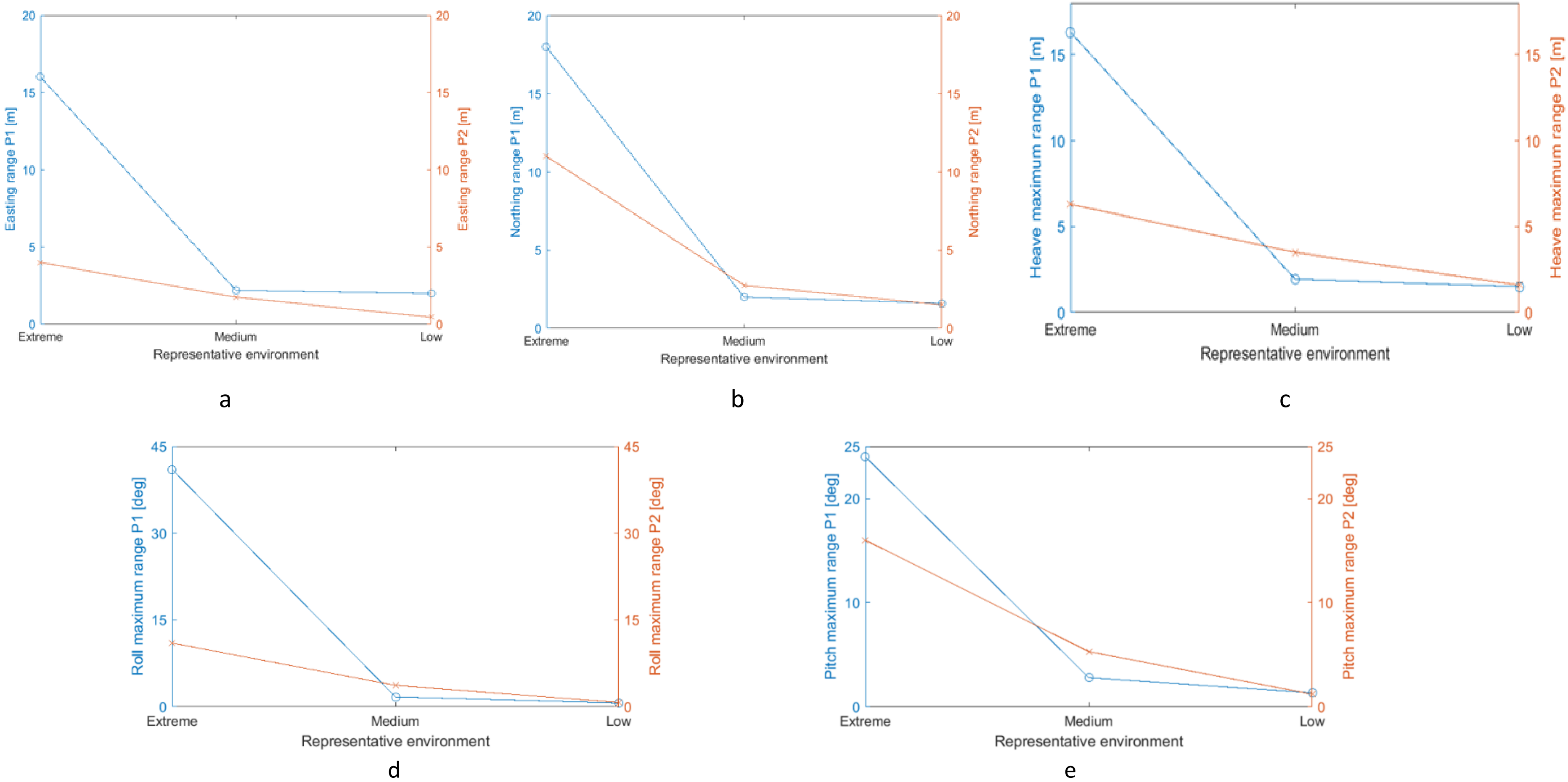


FIGURE 15: COMPARISON BETWEEN MOTION BEHAVIOUR OF MARMOK IN EXTREME CONDITION BETWEEN DP1 AND DP2; A) HORIZONTAL MOTION (EASTING) B) HORIZONTAL MOTION (WESTING), C) HEAVE, D) ROLL , E) PITCH

Generally a reduction in motion (figure 6a-e) and tension was observed for extreme sea conditions. Hereby, the tension was found to be reduced by ~50% during phase 2, compared to tension measured at similar extreme environmental condition during phase 1 (figure 7, 8).

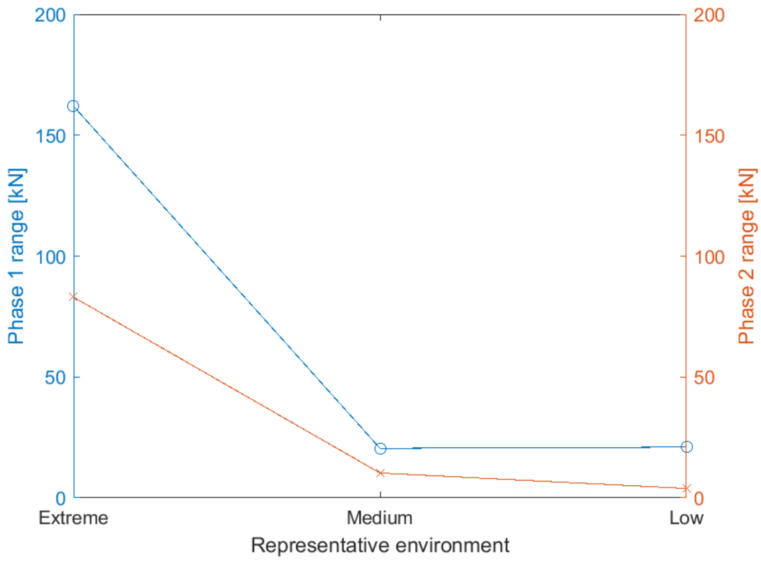


FIGURE 16: COMPARISON OF THE RANGE OF TENSION FOR DP1 AND DP2 DEPLOYMENTS

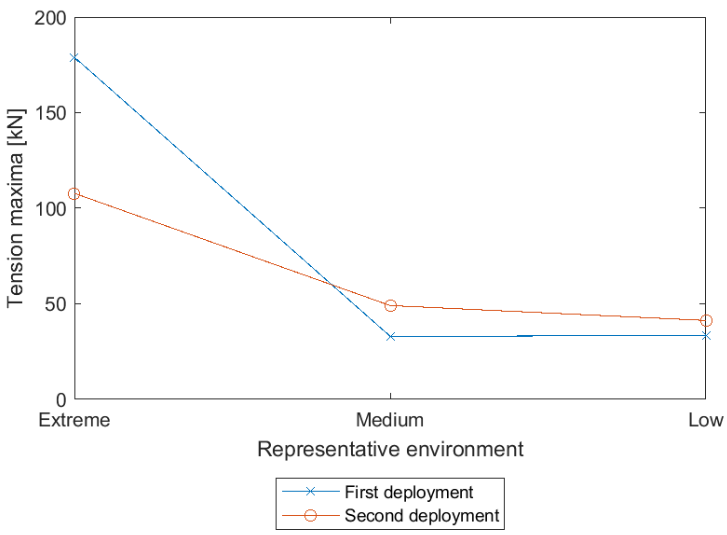


FIGURE 17: AVERAGE MAXIMA FOR MARMOK TENSION IN DP1 AND DP2 DEPLOYMENTS

3.3.4 KEY FINDINGS

- Assessment of elastomeric mooring component (novel component) at small scale and full scale informed about the important in behavior and durability. The steps implemented helped to inform the certification processes, reduced risk and enabled to decide on final design parameters.
- Accurate simulation results are sensitive to 'Start (run-up) Time' and 'Duration' of model simulation
- No conclusive recommendation can be made to 'Number of wavelets sensitivity'; however, the study investigation did illustrate the fact that larger crest events can occur by varying the number of wavelets.
- Variation in number of wavelets illustrated the fact that larger crest events can occur by varying the number of wavelets questioning the suitability of simulations based on 100 wavelets.
- A monotonic nature variation in peak tensions was found by individually adjusting the Cd and Ca values per body.
- A 20 'Seed Analysis' evaluated a design tension from 20 independent short duration analyses. The correlation between peak wave crest and peak tension was observed to be poor.
- Time Step sensitivity assessment showed that the point in time when the peak event occurred is disproportionately sensitive to the Time Step used.
- Element density sensitivity - These tests did not show convergence of the peak tension event (point in time and magnitude) with increased element density.
- Identify the potential causes of discrepancies between the numerical model simulation results and field data as a result of environmental input constrains and analysis method;
- Validated/calibration of numerical simulation is an essential part in the assessment of the MARMOK device using Karratu mooring system;
- Horizontal motion in Northing and Easting were found to be reduced during phase 2;
- Heave motion was reduced for the extreme environment condition during phase 2, limited effect was observed for low and medium environmental condition;
- Roll motion was reduced for the extreme environment condition during phase 2, limited effect was observed for low and medium environmental condition;
- Pitch motion was reduced for the extreme environment condition during phase 2, limited effect was observed for low and medium environmental condition;
- The tension range was reduced for extreme, medium and low environmental condition during phase 2. The tension was found to be reduced by ~50% during phase 2, compared to tension measured at similar extreme environmental condition during phase 1.

4. RECOMMENDATIONS

Based on outcomes of the field demonstration various recommendation can be made:

- Introduction of novel (new) components requires inclusion of high safety factors to address higher risk element; standards should also enable the option to assess performance of novel components through a rigid certification process that should enable avoid requirement of higher safety factors.
- Uncertainties in unknown components requires performing a detailed component FMEA to deduce cumulative Risk Priority Numbers (RPN);
- If novel mooring components and configurations are used, larger safety factor must be applied to ensure structural integrity due to increased risks;
- Fully dynamic simulations need to be performed to assess coupled behaviour between condition (mooring) monitoring system (CMS) and moored system;
- CMS designs need to include enhancement of components to reduce loss of data due to corrosion and marine fouling;
- The CMS should at no time compromise the main mooring configuration and sacrificial should be designed into the CMS;
- For appropriate risk mitigation of novel components, it is recommended that numerous component and performance test campaigns must be run;
- Fatigue factors must be assessed and cable clashing and minimum bending radius identified for the CMS and auxiliary power for the DAQ.
- If possible mooring loads should be monitored close to the floating device to avoid long cable routs through open water;
- Fully dynamic mooring simulations should always performed during design phase;
- Marine growth has a significant impact and it is recommended that this is appropriately incorporated in the modelling process particularly for long-term deployments for the longer term analysis.
- Different safety factors should be considered based on risk criteria, where higher uncertainties should demand higher safety factors.
- Simulation accuracy is dependent on simulation length, occurring of peak wave crest, variation in number of wavelets, but not to sensitivity related to time step or element density;
- An appropriate understanding of the response of the WEC, mooring line tension, number of elements, and simulation length is required before committing to a peak design tension.

5. REFERENCES

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