Open Sea Operating Experience to Reduce Wave Energy Costs

Deliverable D2.2

Mooring Open-Sea Operating Data Analysis

Lead Beneficiary	University of Exeter
Delivery date	2019-07-30
Dissemination level	Public
Status	Approved
Version	1.2
Keywords	Wave energy converter; Mooring; Monitoring; Physical Testing; Numerical modelling.

This project has received funding from the European Union's Horizon 2020 research and innovation programme under grant agreement No 654444

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Document Information

Grant Agreement Number	654444
Project Acronym	OPERA
Work Package	WP2
Task(s)	T2.4
Deliverable	D2.2
Title	Mooring Open-Sea Operating Data Analysis
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File Name	OPERA_D2.2_Mooring open-sea data analysis_UNEXE_20190621_v1.2.docx

Change Record

Revision	**Date**	**Description**	**Reviewer**
0.1	03/05/2019	Initial version	WP partners
0.3	12/05/2019	Working draft	L. Johanning
0.5	16/05/2019	Final draft for review	Pablo Ruiz-Minguela
0.9	27/05/2019	Integrate review comments	L. Johanning
1.0	30/05/2019	Final version for the EC	EC
1.1	21/06/2019	Hyperlinks corrected in figure list	EC
1.2	30/07/2019	Integrate Idom´s comments	B. de Miguel

EXECUTIVE SUMMARY

This document represents Deliverable 2.2 (D2.2) 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 Exeter Tether elastomeric tether, through a combination of comprehensive numerical modelling, an open sea demonstration programme and a dedicated component bench testing programme. This objective is achieved by conducting a comparative analysis of the results from numerical models and open sea demonstration of polyester mooring ropes in Deployment Phase 1 (P1) and two elastomeric tethers in Deployment Phase 2 (P2) used in the Karratu mooring system.

There are two major differences in the layout between P1 and P2. Firstly, the umbilical for P1 was at the lee side whereas it was moved to the upwind direction for P2. Secondly, the polyester mooring lines at the wave-facing end were changed to Exeter tether in P2. The numerical model was adjusted to account for these changes in mooring configuration between the two deployment phases.

An OrcaFlex model of the moored, spar-type, power take-off buoy produced by Oceantec-Idom is used for modelling the wave energy converter (WEC) response in multiple environments. This model is then exposed to convergence and robustness studies and the basic response of the WEC for Phase 1 deployment is presented. An investigation into the divergence of simulated response from empirical results is conducted followed by an investigation into the large yaw rotations. This is done to identify ways to modify the model so that the large yaw rotations are reduced; hence identify which parts of the model require further improvement to address the yaw motions accurately. Finally, the OrcaFlex model is validated using MARMOK measurements for environments in both Phase 1 and Phase 2 deployments to explore differences in the structure.

The OrcaFlex simulations for P1 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 P2 utilises a shorter record of field data collected between 15/11/2018 and 28/01/2019.

The two deployment phases, Phase1 and Phase 2, were initially independently analysed and secondly results were compared for similar environmental conditions. 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 environmental conditions that occurred during Phase 1 and Phase 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.

The comparison is conducted based on outputs such as the translational and rotational motion as well as mooring tension.

KEY FINDINGS:

- 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.

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ABBREVIATIONS AND ACRONYMS

ALS	Accidental Limit State
ADCP	Acoustic Doppler current profiler
CMS	Condition Monitoring System
COG	Centre Of Gravity
FLS	Fatigue Limit State
FOS	Factor Of Safety
MBL	Minimum Break Load
OWC	Oscillating Water Column
P1,2	Phase 1, 2
ULS	Ultimate Limit State
WEC	Wave Energy Converter
WP	Work Package

1. INTRODUCTION

This document is prepared for Deliverable 2.2 of WP2 of the OPERA project. In this introduction some background information is provided setting the work of WP2 within the context of the OPERA project. This is followed by the aim of the deliverable, brief comparison between P1 and P2 and the layout of this report.

The OPERA project saw the open sea demonstration of two mooring innovations deployed with the MARMOK wave energy converter. The two mooring innovations are a shared mooring system (Karratu) and an elastomeric tether (The Exeter Tether). As detailed in the OPERA Grant Agreement, the use of shared mooring systems in aquaculture has reduced mooring costs by up to 50% and similar gains are expected in wave energy applications. Laboratory results, validated with at sea data, demonstrate a potential load reduction of over 70% when using the Exeter Tether, this would translate to cost reduction of the same order for the mooring lines, as well as greatly enhancing survivability with respect to a failure mode that is a central technical challenge for wave energy: low-cycle fatigue of mooring connections.

The aim of WP2 is to de-risk these two mooring innovations. Specific objectives for WP2 are:

- Specify design requirements for a mooring Condition Monitoring System (CMS)
- Design, assemble and incorporate the CMS and the elastomeric tether in the shared mooring
- Design, manufacture and bench-test a novel elastomeric tether
- Evaluate shared mooring open-sea operation with and without the elastomeric tether

The specific requirements of Deliverable 2.2 are defined in the OPERA Grant Agreement:

> ***D2.2 Report: Mooring open-sea operating data analysis.*** *(Month 38). Analysis of shared mooring demonstration with and without elastomeric tether, including data quality assessment, logical presentation and interpretation, documentation to data management.*

This report caters to *Objective 2* to de-risk innovations that lower mooring cost over 50% and enhance survivability using output from *T2.1 and T2.2.* The comprehensive dynamic behavior investigated for *T2.1* aided with field data gathered in *T2.2* from open sea testing in two configurations allows for a comparative analysis of the mooring system with and without the elastomeric tether.

This document outlines the benchmarking for the open sea demonstration through a fully coupled simulation design assessment including slow drift motion, nonlinear coupled behaviour, dynamic load characteristics and potential load reduction. It then uses numerical modelling and field data from Phase 1 and Phase 2 to identify the influence of the integration of the elastomer component into the second demonstration phase.

Phase 1 tested the Karratu mooring system independently whilst Phase 2 incorporated the Exeter Tether into the Karratu mooring system. Each deployment phase was scheduled for 1 year.

Originally generated by Oceantec-Idom, the numerical model was revised as part of this deliverable based on recommendations from partner institutions. Using field measurements (wave buoy measurements, device responses and mooring tensions) validation of the numerical model was performed to improve its application to marine operation planning and investigations into array configurations with multiple devices.

1.1 PHASE 1 DEPLOYMENT

MARMOK was successfully deployed for a year for Phase 1 (P1) with the mooring data register starting on 13/12/2016 and ending on 11/12/2017.

Figure. 1-1 displays the arrangement of the device response and mooring tension monitoring equipment for P1.

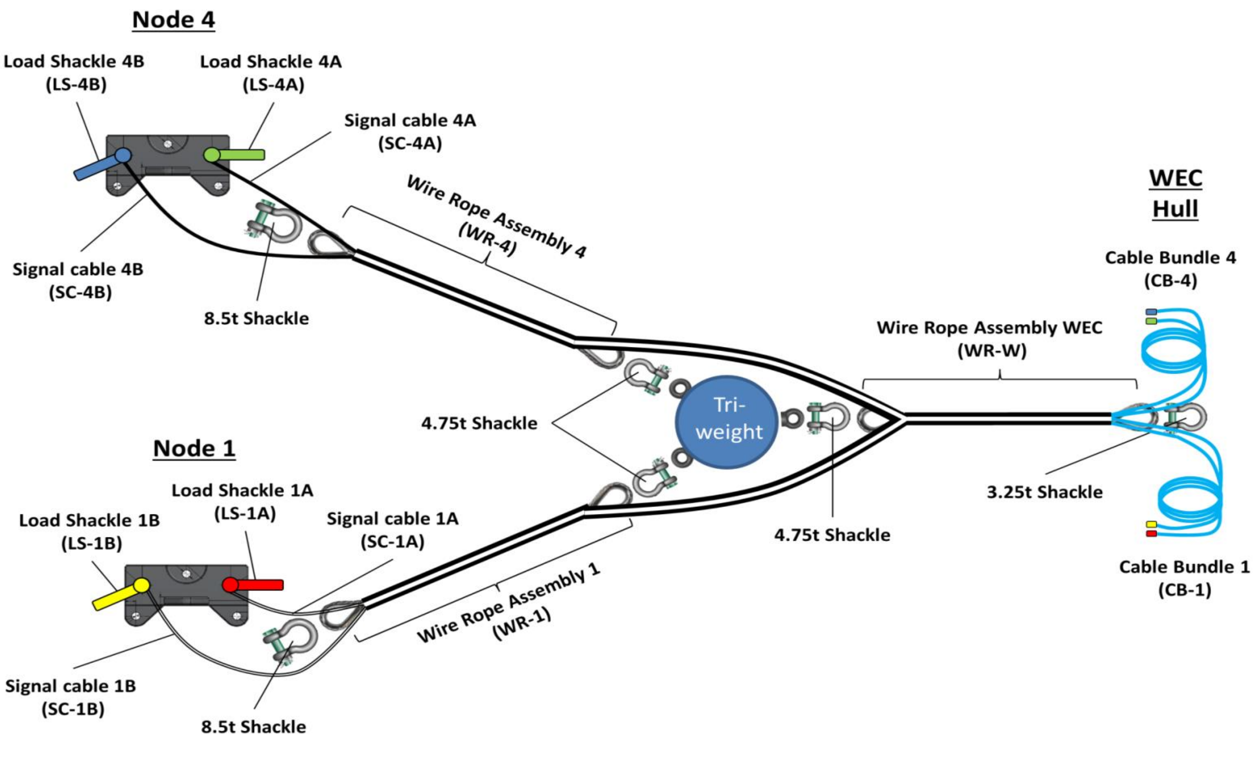


FIGURE. 1-1. LOAD MEASUREMENT ARRANGEMENT P1

For the purposes of the validation three distinct environmental situations have been used for P1:

i. Low environment at 10:00 on the 6/05/17
ii. Medium environment at 12:00 on the 28/06/17
iii. Extreme environment at 20:00 on the 28/06/17

The validation process has focused on the following parameters:

- Easting and Northing of the radar antenna
- Heave at the CoG
- Roll and Pitch of the MARMOK
- Tension at the upper end of the catenary of Line #1

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

The reason for these differences have been discussed in the report and following points have been made:

- The pressure in the chamber may influence the mean draft of the MARMOK and hence also 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 ENV103 and ENV104.
- 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.

To improve the corroboration, the assessment of the influence of the pressure in the chamber is recommended.

1.2 PHASE 2 DEPLOYMENT

The length of recorded field data of P2 was reduced to a two-month period whereby the data register commenced on 15/11/2018 and lasted till 28/01/2019.

The arrangement of the device response and mooring tension monitoring equipment was altered between the two deployments.

For Phase 2 (P2) the MARMOK-A5 device and Karratu mooring system were modelled using load cases according to DNVGL-OS-E301 design criteria in order to determine the scale of the elastomeric tethers used in the project. Additional modelling of the device and mooring system allowed for the determination of a suitable configuration for the load monitoring system. Due to constraints imposed by the structural integrity of the hull, the initial location (with the load shackles adjacent to the hull) was moved to the corner nodes. Detailed dynamic simulation work was carried out to assess the load monitoring system to ensure that it was suitable for the task and would not interfere with the mooring system or device.

The arrangement for P2 is shown in Figure. 1-2. For this deployment, the motion instrumentation was fully functional, however, the tension measurement system was limited to 1 of 4 channels.

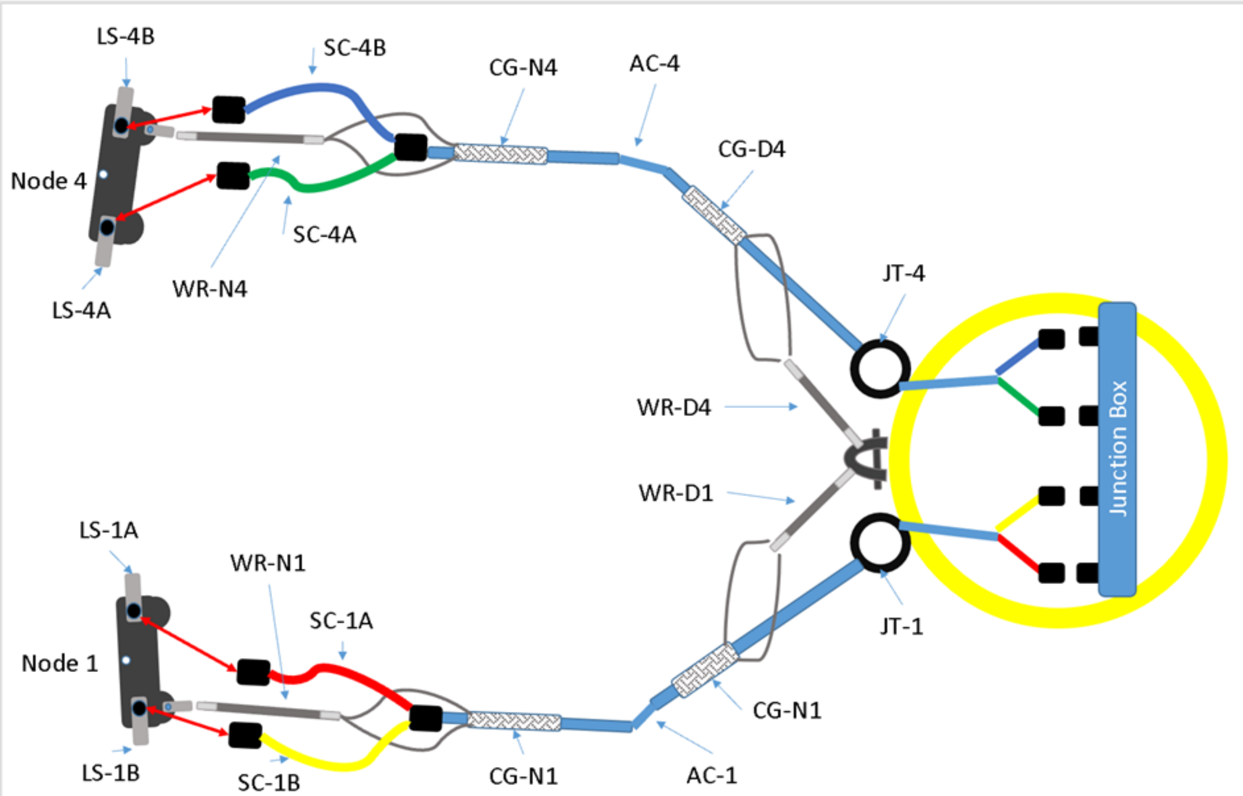


FIGURE. 1-2 LOAD MEASUREMENT ARRANGEMENT P2

Three environments with similar conditions to P1 deployment were chosen from P2 to compare the two mooring configurations and identify variation in the response characteristics of MARMOK due to the use of the Exeter Tether. The second deployment model selected Hs and Te as close as possible to the first deployment to reach a comparable environment between both cases.

For the purposes of the validation three distinct environmental situations have been used for P2:

i. Low environment at 13:00 on 30/12/2018
ii. Medium environment at 14:00 on the 23/12/2018

iii. Extreme environment at 11:00 on the 14/12/2018

Field data and model results for these environments were compared with those from P1 and

1.3 LAYOUT

The key sections of this deliverable along with their respective contributions are outlined to inform the layout of the deliverable.

Section 2 details the modelling and analysis of the moored, spar-type, power-off take buoy. A review of the model provided by Oceantec-Idom and an investigation and resolution of the non-zero sway offset and yaw rotation that have been identified in the static equilibrium.

Section 3 presents a set of initial investigations into the robustness of the analysis procedure and model definition and improvements implemented in the model. The simulation length, element density, Cd and Ca, seed number, long run and time step sensitivities are investigated in Section 3.1. Section 3.2 investigates the variation in WEC and mooring response based on the numerical models particularly the number of elements in the mooring line and size of time step. Section 3.3 presents an investigation into the occurrence of large yaw rotations of the MARMOK WEC as observed in 3-hour mooring simulations. It also highlights elements in the model that can assist in reducing the excessively large rotations

Section 4 describes the environmental parameters associated to the validation study of the modelled OrcaFlex data with open sea data for P1 and P2 deployments.

Section 5 summarises the aspects of the validation of the numerical model of the moored MARMOK wave energy converter for the two distinct environmental situations for P1 and P2. These include motion response, mooring load response and uncertainties in the validation parameters.

Finally, Section 6 presents the comparative analysis of MARMOK motion and Line 1 tension between the two deployment phases to highlight the significance of the use of the Exeter Tether in the mooring configuration.

Much of the information presented in this Deliverable has been circulated to OPERA Partners in the form of Technical Notes throughout the first phase of the OPERA project and where relevant, these Technical Notes will be referred to.

2. SPAR BUOY MODEL SET-UP

2.1 REVIEW OF OCEANTEC-IDOM'S ORCAFLEX MODEL

The principal dimensions of the MARMOK spar-buoy are presented in Figure. 2-1 and Table 2-1.

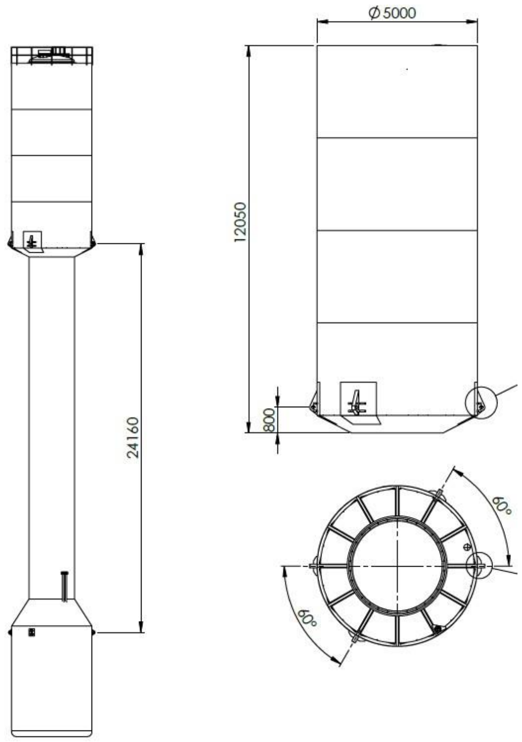


FIGURE. 2-1 MARMOK SPAR-BUOY

TABLE. 2-1 MARMOK-A-5 DEVICE PRINCIPAL PARAMETERS

Mass (t)	Total Volume (m3)	Diameter max (m)	Diameter min (m)
162.2	276	5	2.85

Device is modelled by two 6D buoys, one corresponding to the buoy itself and other to the oscillating water column. Through a set of links OWC movements are restricted only allowing the one parallel to buoys axis of revolution. In the next figures both bodies models are presented.

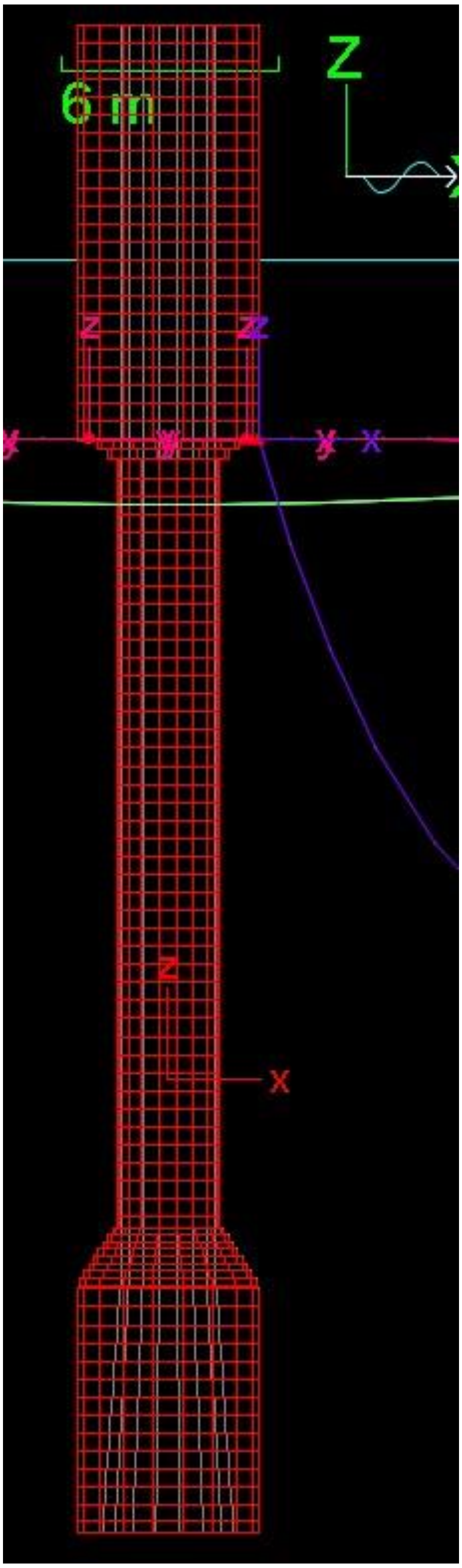


FIGURE. 2-2 MARMOK 6D BUOY

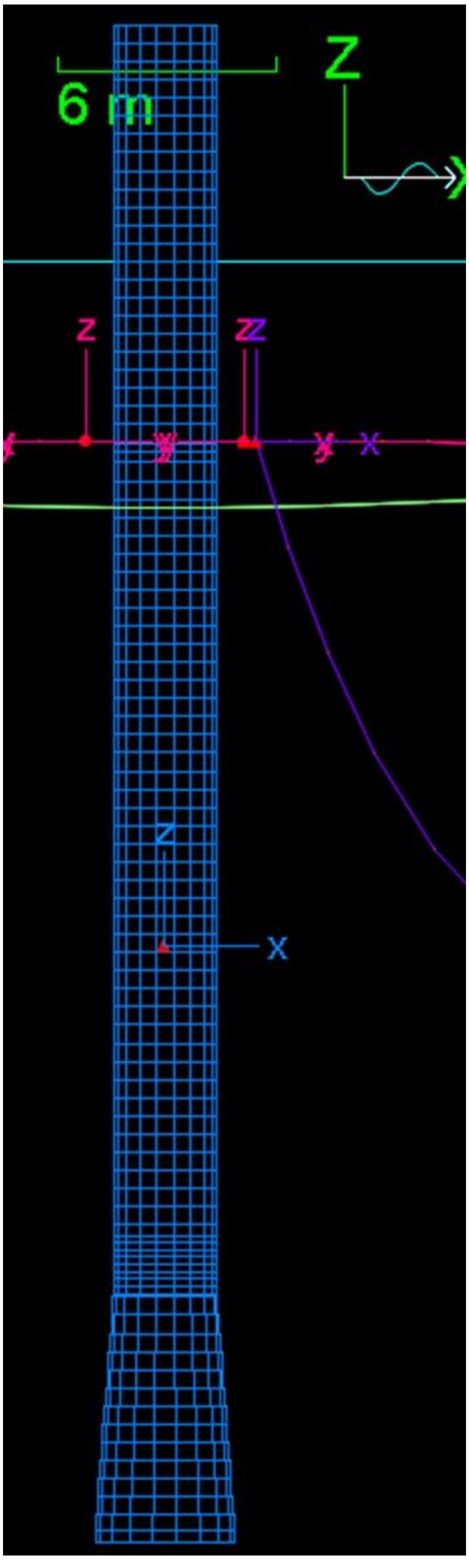


FIGURE. 2-3 OWC_V2.2 – 6D BUOY

2.1.1 ENVIRONMENT

2.1.1.1 WAVES

Wave parameters are presented in Figure. 2-4.

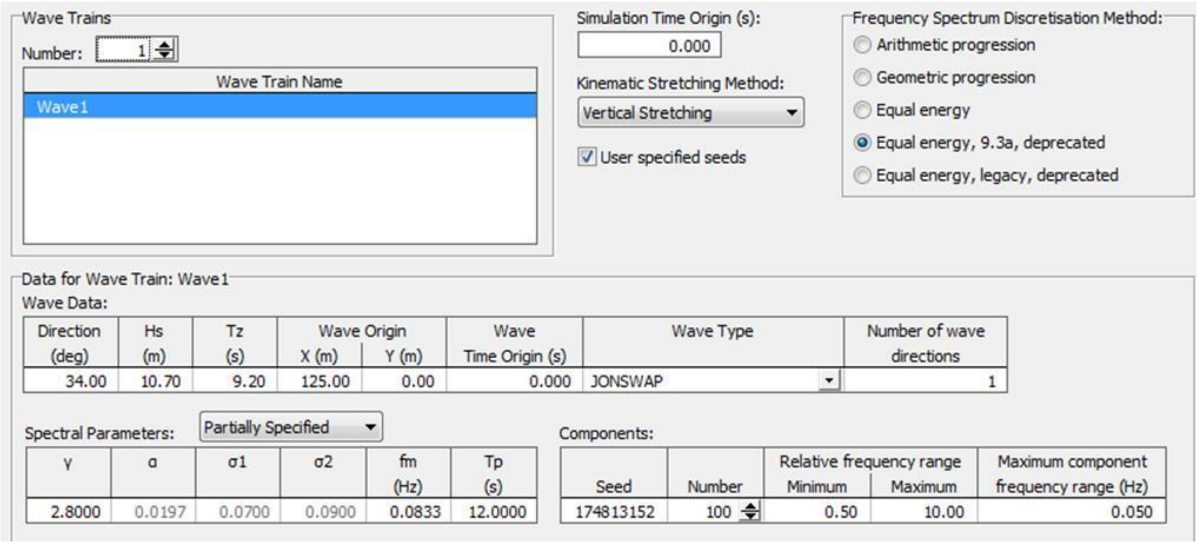


FIGURE. 2-4 ENVIRONMENT – WAVE

2.1.1.2 A UNI-DIRECTIONAL SEA IS APPLIED CURRENT

The current data specification is presented in Figure. 2-5 and the current profile is presented in Figure. 2-6.

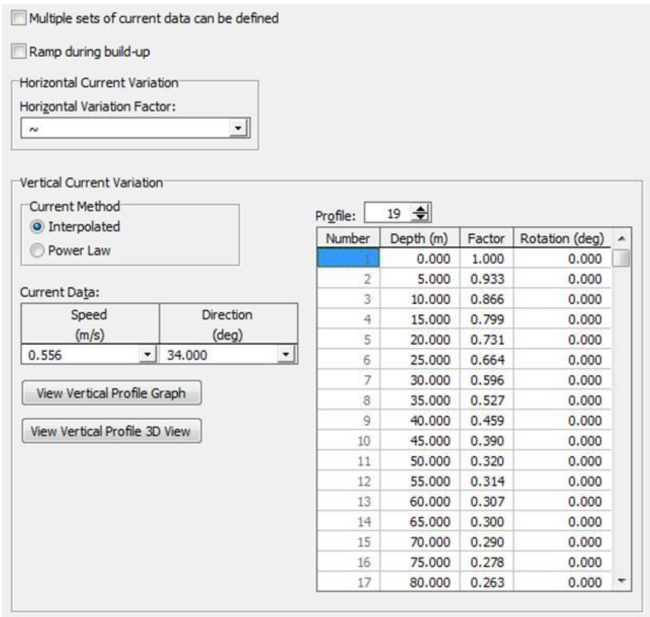


FIGURE. 2-5 ENVIRONMENT DATA – CURRENT

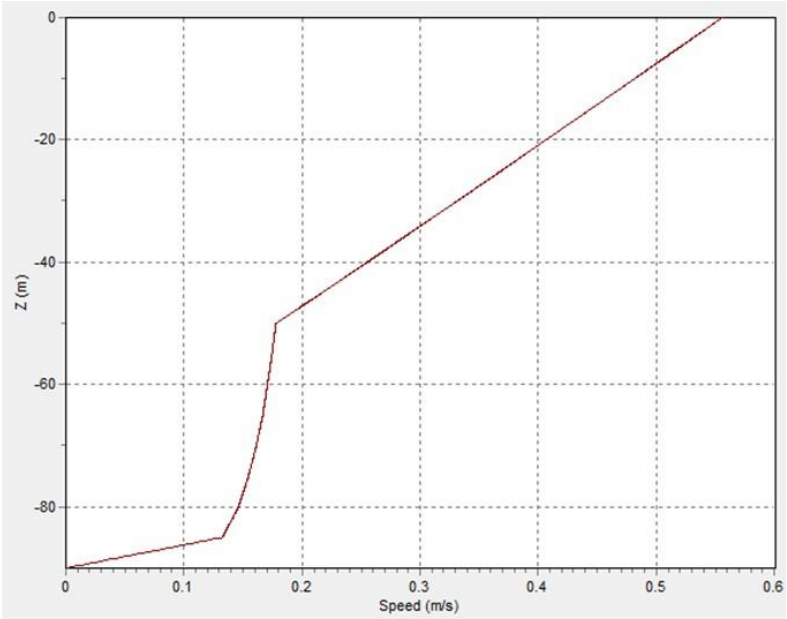


FIGURE. 2-6 ENVIRONMENT DATA – CURRENT PROFILE PLOT

2.1.1.3 **WIND**

The wind data specification is presented in Figure. 2-7.

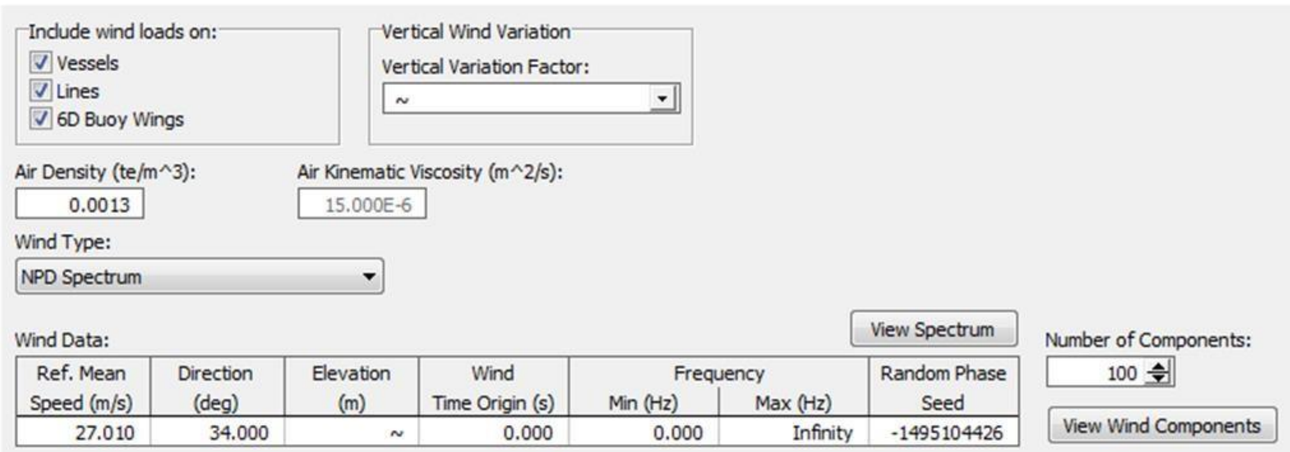


FIGURE. 2-7. ENVIRONMENT DATA - WIND

2.1.1.4 **SEABED**

Some uncertainties are given for the purposes of specifying the appropriate type and size of anchor; these are:

- availability of geophysical or geotechnical data for the BiMEP site,
- the type and depths of soil layers at each of the proposed anchor positions.

2.1.2 MOORING SYSTEM DESCRIPTION

The Karratu mooring system restrains the MARMOK wave energy converter. It is designed to restrain the MARMOK to stay on station in the locality of the power off-take cable. However, it also designed not to restrain the wave frequency motion response of the MARMOK, so that the wave energy conversion is as effective as possible.

2.1.2.1 GENERAL DESCRIPTION

MARMOK is held in place by a compliant mooring system. The mooring consists of a Karratu mooring arrangement that is supported at its external corners by a more conventional catenary mooring leg terminating at an anchor at the seabed.

The Karratu mooring arrangement consists of a rectangular arrangement of wire in plan view. At each corner of the rectangle a mooring line made of polyester runs horizontally towards the centre of the rectangle and is attached to the fairlead on the sideshell of the MARMOK. Each corner of the rectangular plan of wire is supported by a buoy at the surface. The buoy also supports the conventional catenary leg outboard of the Karratu arrangement. The catenary mooring legs consist of chain and fibre components. The fibre component terminates at the corner of the Karratu rectangle supported by the surface buoy. The mooring system is presented in Figure. 2-8 and Figure. 2-9. The component details of the mooring system are presented in Section 2.1.2.2, and the Karratu geometry are presented in Section 2.1.2.3.

The Karratu mooring system is intended to be cellular so that several WEC devices can share a common mooring system.

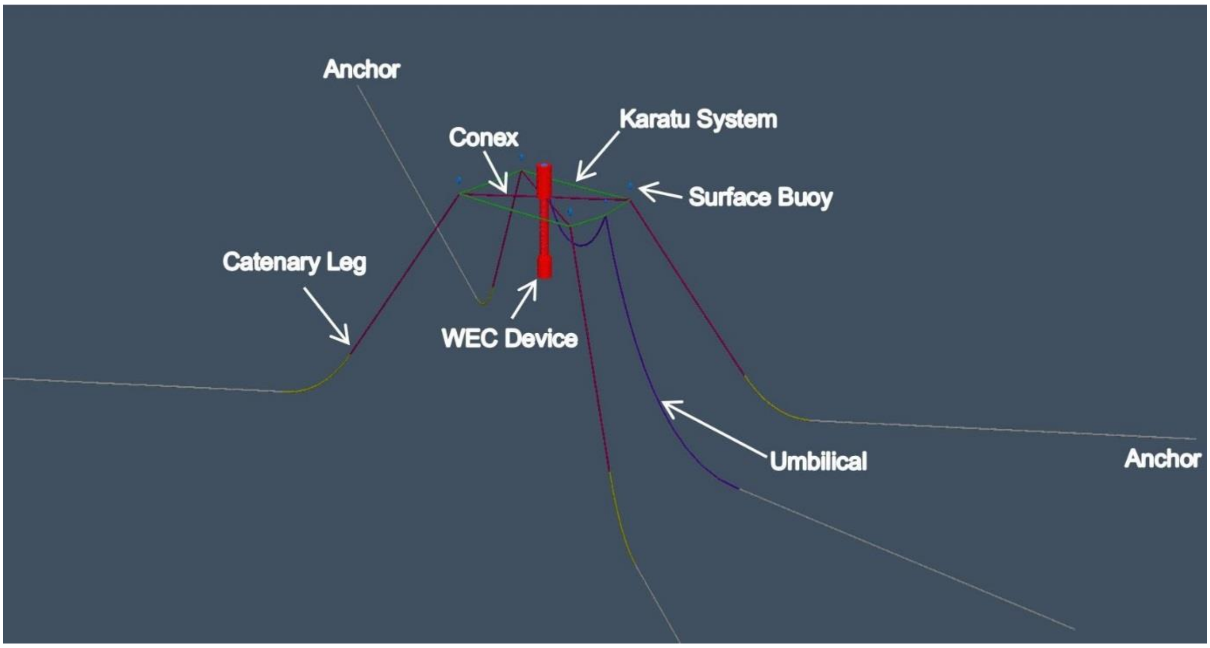


FIGURE. 2-8 ISOMETRIC VIEW OF MOORING SYSTEM

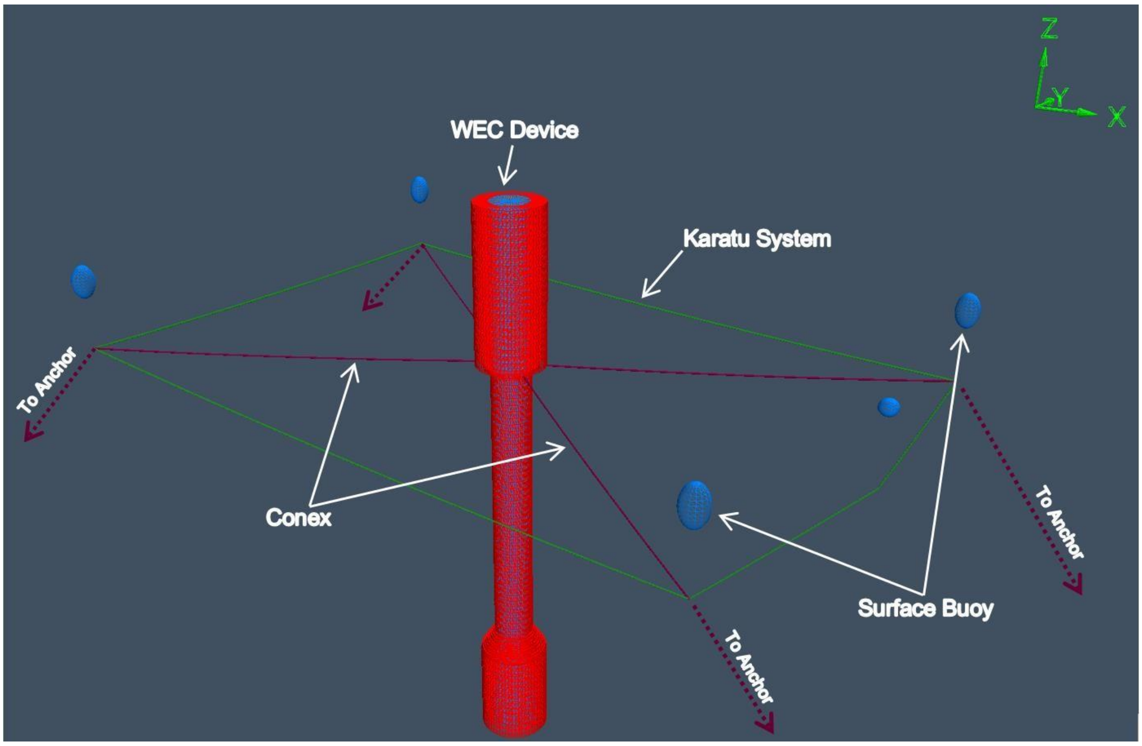


FIGURE. 2-9 CLOSE-UP VIEW OF KARRATU SYSTEM CONNECTION AND WEC DEVICE (UMBILICAL OMITTED)

2.1.2.2 COMPONENT TYPES

The WEC's mooring system consist of various components, the detail of which are presented in Table. 2-2.

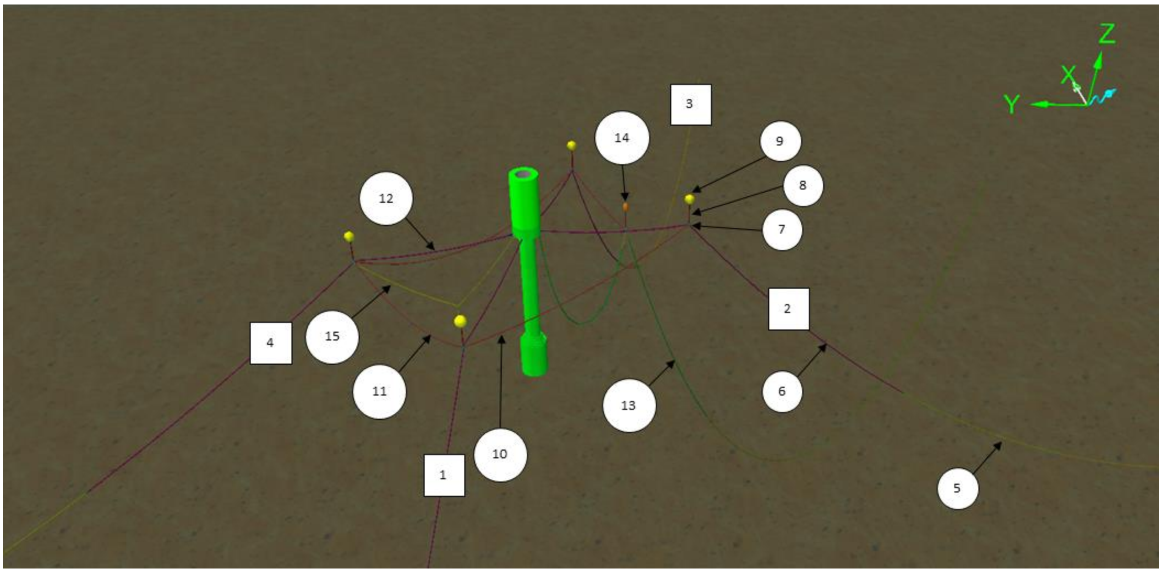


FIGURE. 2-10 MOORING SYSTEM COMPONENTS IDENTIFICATION

TABLE. 2-2 MOORING COMPONENTS DETAIL (DIMENSIONLESS) ACCORDING TO FIG. 2-10

#	Item	Diameter	Max length	Dry weight
1	Mooring Limb 1	*Mooring assembly: Detailed example Item 2*		
2	Mooring Limb 2	*Mooring assembly: Comprising components 5, 6, 7, 8, 9 and 12.*		
3	Mooring Limb 3	*Mooring assembly: Detailed example Item 2*		
4	Mooring Limb 4	*Mooring assembly: Detailed example Item 2*		
5	Catenary chain (studlink)	1.0	1.0	1.0
6	Catenary rope (polyester)	1.82	0.157	0.094
7	Connecting Node	-	-	1.0
8	Buoy chain (studless)	0.73	0.009	0.494
9	Pennant buoy	36.36	0.004	8.182
10	Cell line C (wire rope)	0.36	0.116	0.023
11	Cell line B (wire rope)	0.36	0.072	0.023
12	Connex rope (polyester)	1.82	0.06	0.094
13	Umbilical	1.14	~	0.15
14	Bend restrictor assembly	-	-	14.478
15	Load shackle cable support system	See Section 1.1		

2.1.2.3 KARRATU AND CATENARY LEG LAYOUT / MAKE-UP

The WEC centre is located 129.8m in X-direction and 0.0m in Y-direction from the Global Origin as shown in Figure. 2-11.

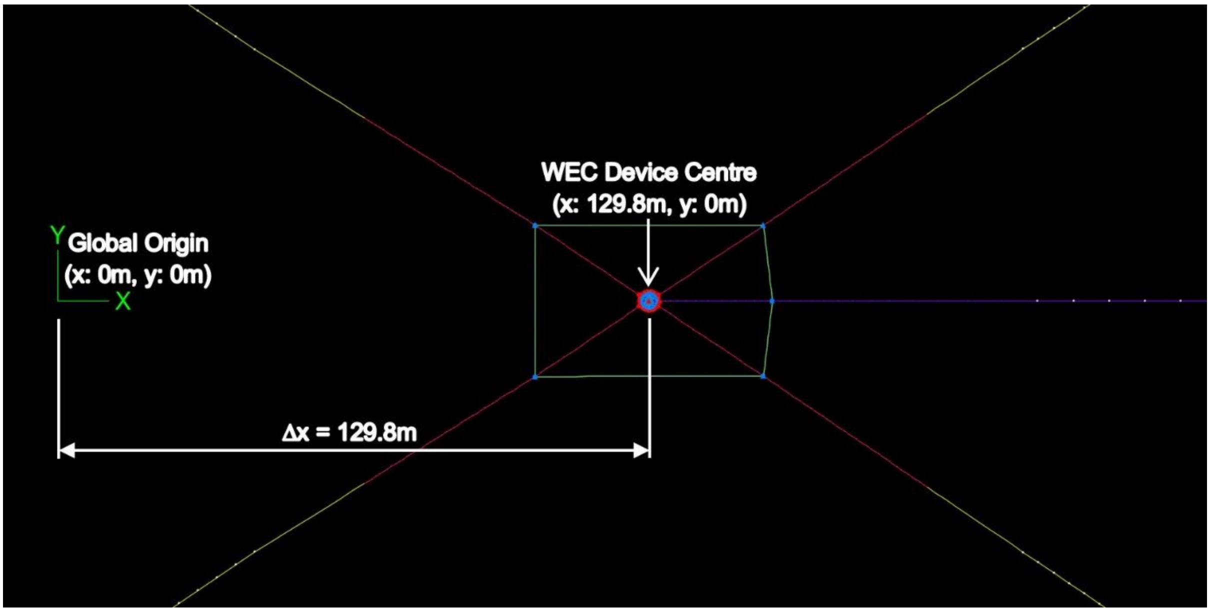
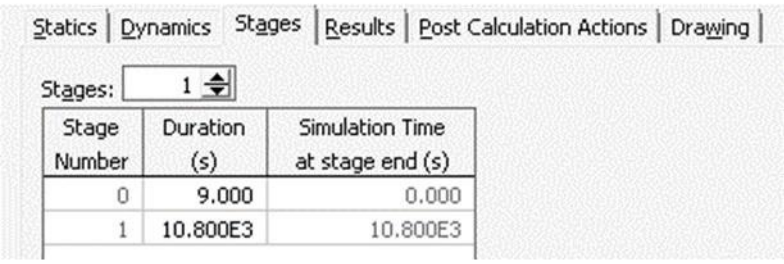


FIGURE. 2-11WEC POSITION W.R.T. GLOBAL ORIGIN

2.1.3 SIMULATIONS

2.1.3.1 STAGES

The stages are presented in Figure. 2-12.



Stage Number	Duration (s)	Simulation Time at stage end (s)
0	9.000	0.000
1	10.800E3	10.800E3

FIGURE. 2-12 STAGES OF ANALYSIS

2.1.4 WAVE ELEVATION

The wave profile at X = 133.7m, Y=0.0m is presented in Table. 2-3:

TABLE. 2-3 WAVE PROFILE EVENTS

Event	Value (m)	Global Time (s)
Largest Rise	18.06	8961.19
Largest Fall	17.3	3742.59
Highest Crest	9.36	3742.59
Lowest Trough	-10.48	8961.19

A 100 second simulation commencing at 3690sec is presented in Figure. 2-13, demonstrating the highest crest event for the seed in the *.dat file.

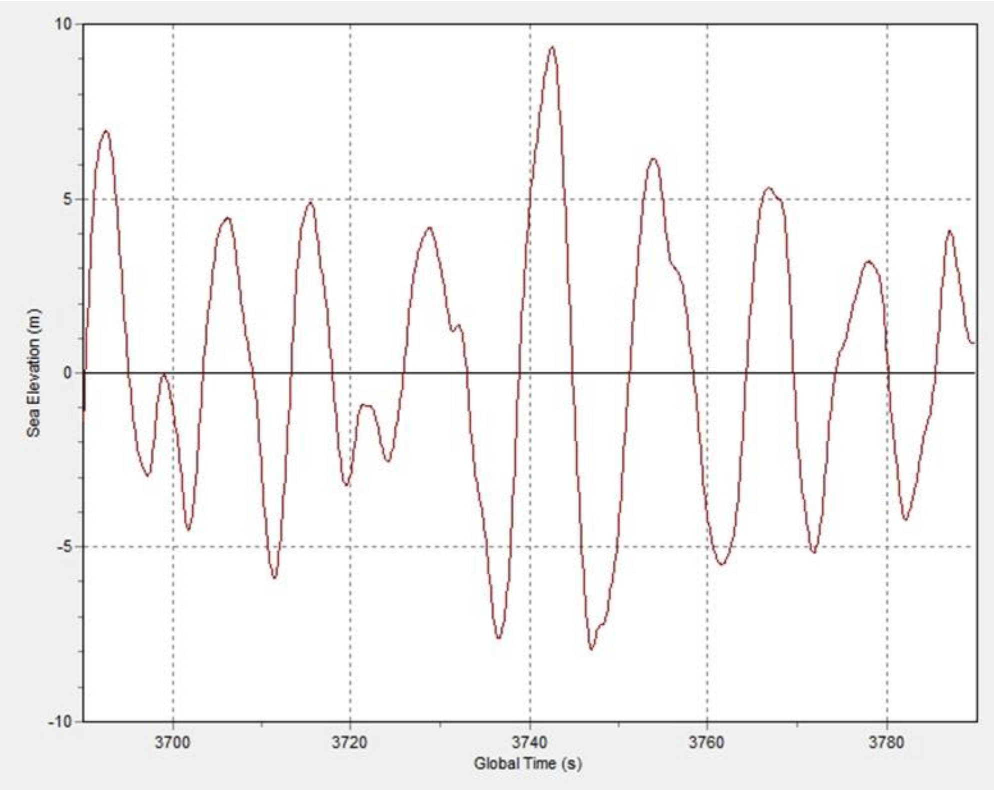


FIGURE. 2-13. WAVE ELEVATION

2.1.4.1 DYNAMIC RUN-TIME

The position and rotation of the MARMOK spar-buoy (CoG) are presented in Figure. 2-14.

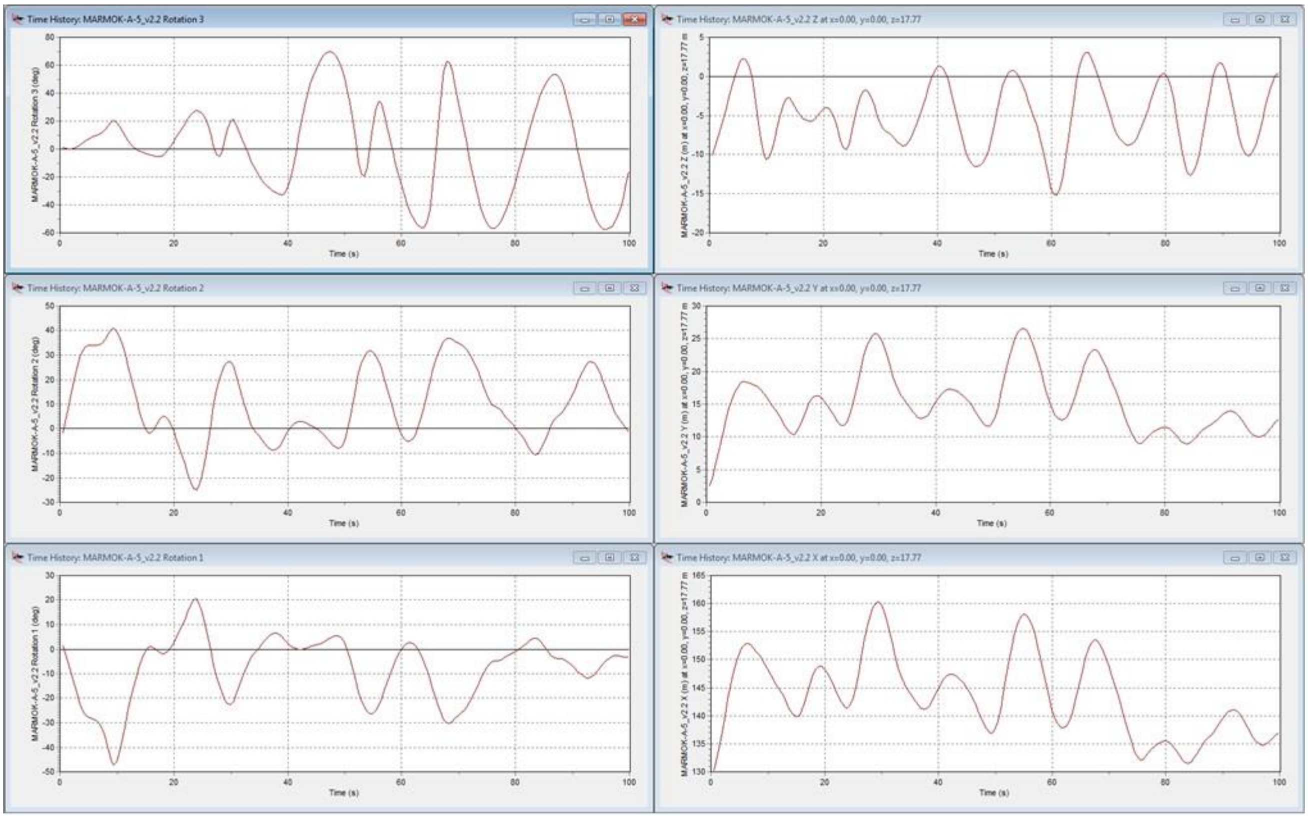


FIGURE. 2-14 POSITION AND ROTATION OF THE MARMOK SPAR BUOY

The end force (tension) along with layback, and wave elevation are presented in Figure. 2-15.

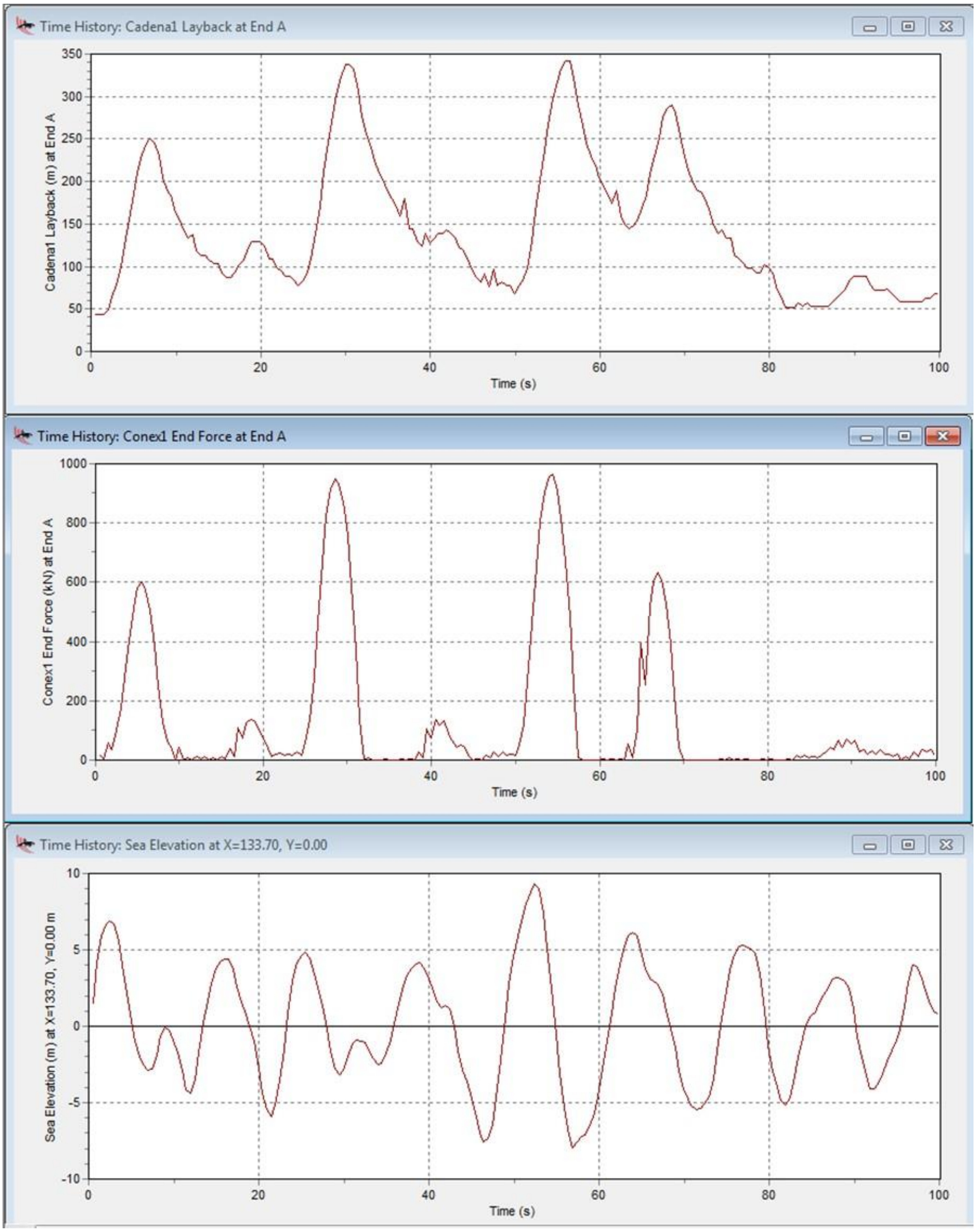


FIGURE. 2-15 END FORCE, LAYBACK AND WAVE ELEVATION

In this short simulation the peak mooring line load was 963.7kN. It is noted that the peak load is closely correlated in time to the peak wave elevation, large offsets in X and Y and large rotations R1 and R2 of the MARMOK buoy.

It has not been stated precisely how the 3-hour simulation has been interrogated to derive a design tension. However, it would not be good practice to base the peak tension on one peak event from either a 3-hour simulation or 100sec short simulation. If peak events are being used to develop the design tension, it is recommended that numerous realisations e.g. 20 are analysed.

2.1.5 LAY ANGLE ADJUSTMENT

2.1.5.1 DESCRIPTION OF PROBLEM

It was observed in the static equilibrium of the moored WEC, that the WEC was 'skewed' in the static equilibrium condition. The WEC position was displaced in sway direction (Y-axis) and the orientation was slightly rotated, this condition is depicted in Figure. 2-16. Rotation 1 (about X-axis) is the Roll angle, Rotation 2 (about Y-Axis) is the Pitch angle and Rotation 3 (about Z- Axis) is the Yaw angle of the WEC.

A detail examination has been performed on the OrcaFlex model, and it was found that this anomaly was caused by the 'Lay Azimuth' value in the OrcaFlex lines option. It is desirable to remove this anomaly so as not to influence unnecessary the dynamic analyses.

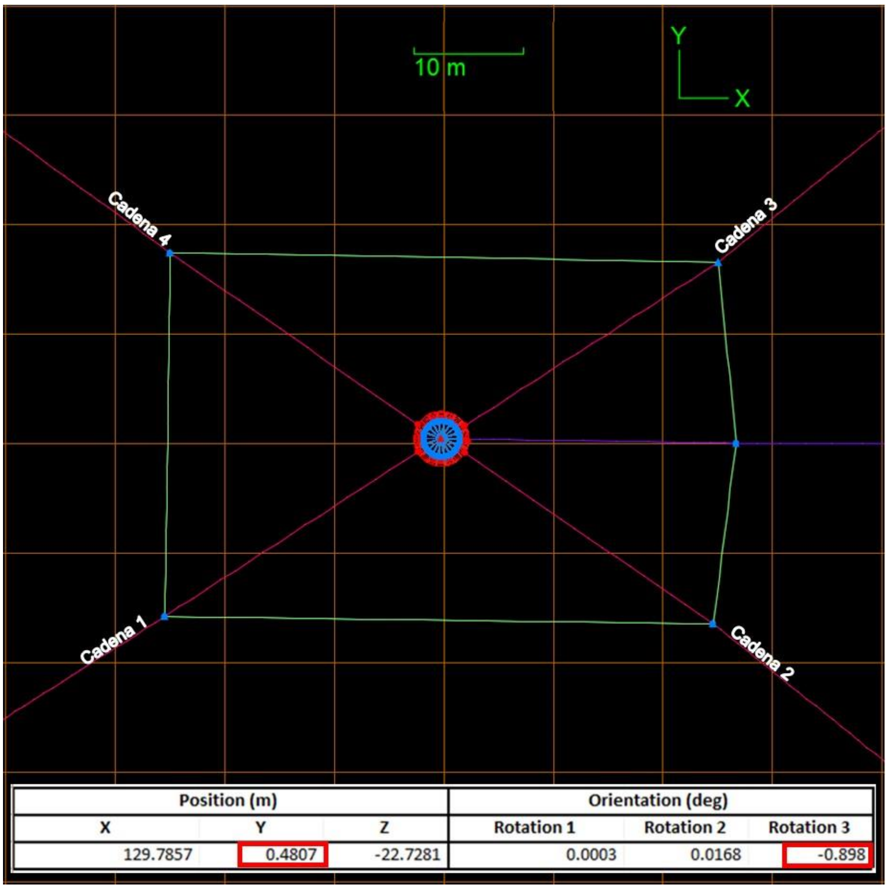


FIGURE. 2-16 STATIC EQUILIBRIUM OF THE SYSTEM – BASE CASE

2.1.5.2 RESOLUTION OF PROBLEM

The default values of 'Lay Azimuth' of the mooring line as defined in the 'Base Case' model were adjusted. These angles are presented in Table. 2-4. The adjusted resolved the non-zero sway offset and yaw (skew) problem, as shown in the Figure. 2-17. The slight trim (Rotation 2) is due to the presence of Umbilical.

TABLE. 2-4 LAY AZIMUTH OF MOORING LINES

Catenary Lines	Lay Azimuth (deg.)	
	Base Case	Adjusted
Cadena 1	34.05	34.00
Cadena 2	148.66	146.00
Cadena 3	211.34	214.00
Cadena 4	326.85	326.00
Conex 1	226.13	225.00
Conex 2	326.22	315.00
Conex 3	46.13	45.00
Conex 4	133.87	135.00

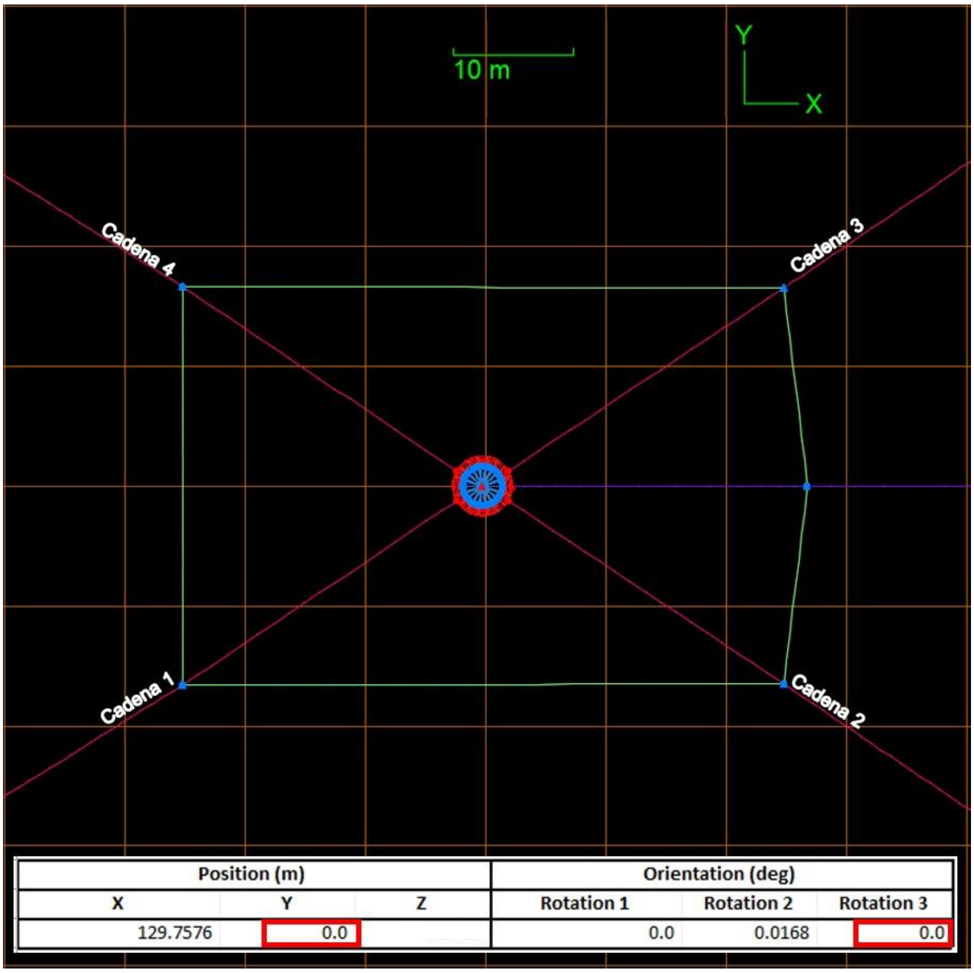


FIGURE. 2-17 STATIC EQUILIBRIUM OF THE SYSTEM – ADJUSTED

3. SENSITIVITY ANALYSIS AND IMPROVEMENTS TO ORCAFLEX MODEL

3.1 CONVERGENCE AND ROBUSTNESS TESTS

This chapter summarises a set of initial investigations into the robustness of the analysis procedure and model definition. The investigations consist of the following tests:

- Simulation Length
- Element density
- Wavelet sensitivity
- Cd and Ca sensitivity
- 20 seed – short simulation
- Long run analyses - 10,800 sec
- Time step sensitivity

Some adjustments were made to the basis model for simplification purposes, and benchmark tests were done.

The initial proposition was that the design tension could be evaluated based on doing a number (e.g. 20) of short duration simulations (e.g. 200sec), each based about a peak crest event. However, the assessment has not been able to demonstrate satisfactory convergence either in the model or analysis, with regards: mesh density, simulation length, time step length, and selection of the peak crest event from any wave synthesis.

This calls into question whether the design tension can be satisfactorily evaluated using the short simulation procedure. It appears that it is not possible to assume that the peak tension occurs in the vicinity of a peak crest.

It would be helpful to have a better understanding of the response of the WEC and mooring line tension to the various modelling parameters (number of elements, start time, duration, element density, time step, number of wavelets) before committing to a peak design tension.

An outline of a work-scope is also described here-in, for discussion purposes.

3.1.1 MODIFICATION TO ORIGINAL MODEL

The original model received from Oceantec-Idom, was modified slightly to remove some undue complexity. A benchmark test was done to demonstrate that the results of the modified models did not change markedly from the original model. The simulation was 200 sec in duration, seed 174813152 (original), and peak wave crest at 3742sec. The models analysed were:

a. Original
b. End Orientations
c. End Orientations without Nodo (Base Case)
d. End Orientations, without Nodo, with Wing

TABLE. 3-1MODIFIED MODEL - BENCHMARK TESTS

Model modification	*Tension (kN)*	*% Diff*
Original	*928.08*	*0.00*
End Orientation	*928.04*	*0.00*
End Orientation no Nodo	*936.88*	*0.01*
End Orientation no Nodo plus Wing	*984.22*	*0.06*

Note 1 - model: End Orientation

Note 2 - line: Conex 1 - End B

The modified model “End Orientation” demonstrated that it gave the same peak tension at Conex 1, End B (MARMOK connection point). However, it was surprising that some variation was observed by removal of the Nodo (3D buoy element).

3.1.2 START TIME – DURATION SENSITIVITY

Using the modified model “End Orientation” a sensitivity study was done using the same seed 174813152 (original), targeting the peak crest event at 3742sec, but commencing the simulation progressively earlier in order to let low-frequency forcing and motion to stabilize. The start time - duration lengths were: 100s,200s, 400s, 800s, 1600s.

TABLE. 3-2 START TIME -DURATION SENSITIVTY

Duration (sec)	Tension (kN)	% Diff
100	963.80	0.04
200	928.04	0.00
400	936.71	0.01
800	941.33	0.01
1600	976.63	0.05

Note 1 - model: End Orientation

Note 2 - line: Conex 1 – End.B

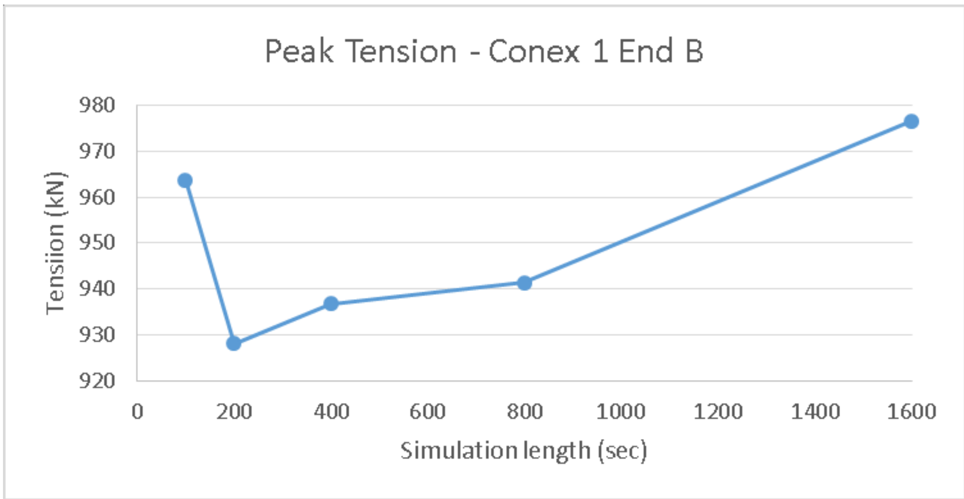


FIGURE. 3-1 START TIME - DURATION SENSITIVITY

This test showed that there was large variability in peak tension evaluations, even after running for 1600sec. This raised the questions: is the short simulation length (200sec) appropriate?

3.1.3 NUMBER OF WAVELETS

Using the modified model "End Orientation", 200s duration, seed 174813152 (original), a sensitivity study was done on number of wavelets.

DNV-RP-C205, section 3.3.2.2 states "The number of frequencies to simulate a typical short-term sea state should be at least 1000."

The sensitivity study was done using the following number of wavelets: 100, 200, 400, 800

No. of Wavelets	Tension (kN)	Wave Crest (m)
100	928.04	9.24
200	1035.25	10.22
400	**1332.71**	**11.45**
800	788.63	9.83

This test is 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, it did illustrate the fact that larger crest events can occur by varying the number of wavelets. This raised the question: are simulations based on 100 wavelets appropriate?

3.1.4 CD AND CA SENSITIVITY – PART A

Using the modified model "End Orientation", 200s duration, seed 174813152 (original), a sensitivity study was done on Cd and Ca by applying the following factors to these parameters: 0.5, 1.0, 1.5, across whole of MARMOK & OWC. This test is inconclusive as no readily identifiable pattern has emerged.

TABLE. 3-3 CD AND CA SENSITIVITY - PART A

Factor on Hydro Parameter	Ca		
Cd	0.5	1	1.5
0.5	1016.3	908	978.3
1	791.3	928.04	985.5
1.5	820.5	855.8	911.7

Note 1 – model: End Orientation

Note 2 – line: Conex 1 – End B

3.1.5 CD AND CA SENSITIVITY – PART B

Using the modified model "End Orientation no Nodo", 200s duration, seed 174813152 (original), a sensitivity study was done on Cd and Ca by applying the following factors to these parameters: 0.5, 1.0, 1.5, on individual contributions from the MARMOK & OWC.

TABLE. 3-4 CD AND CA SENSITIVITY - PART B

Line	Cadena1 - End A (kN)			Conex 1 - End B (kN)		
Factor on Hydro Parameter	0.5	1	1.5	0.5	1	1.5
MARMOK Ca_Axial	978.4	**941.3**	920.4	974.1	**936.8**	912.6
MARMOK Ca_Normal	927	**941.3**	984.7	922.1	**936.8**	976.9
MARMOK Cd_Axial	989.5	**941.3**	952.1	981.4	**936.8**	947.7
MARMOK Cd_Normal	995.8	**941.3**	874.8	987.7	**936.8**	870.2
OWC Cd_Axial	974	**941.3**	922	969.7	**936.8**	917.5

Note 1 – model: End Orientation no Nodo

These tests demonstrated that nearly all variations in Cd & Ca give rise to monotonic variation in peak tensions, except for MARMOK Cd_axial.

3.1.6 20 SEEDS ANALYSIS

Using the "End Orientation model no Nodo", 200s duration, seeds from 100 to 2000 in steps of 100 were used to synthesise irregular seas, from which the crest event was identified.

The following table presents an application of 20 short (200s) simulations to obtain 20 peak tension events, and then using these as a basis for predicting a design tension. This approach is inspired by a Bureau Veritas approach. NB The range on peak tension is very large (861kN), which indicates sensitivity to the response. Also the correlation between peak wave crest and peak tension is poor.

TABLE. 3-5 20 SEED ANALYSIS OF PEAK TENSION

Test no.	Tension (kN)	Wave crest (m)	Rank no.	Tension (kN)
1	1070.2	10.3	**1**	525.4
2	931.4	9.2	**2**	669.6
3	1081.8	10.3	**3**	707.1
4	718.0	8.8	**4**	718.0
5	937.6	9.6	**5**	732.7
6	863.5	10.2	**6**	793.6
7	707.1	10.2	**7**	850.8
8	793.6	10.3	**8**	863.5
9	669.6	10.4	**9**	931.4
10	850.8	10.7	**10**	937.6
11	975.3	11.4	**11**	938.0
12	1206.5	11.8	**12**	948.5
13	938.0	10.7	**13**	975.3
14	732.7	9.5	**14**	985.1
15	985.1	9.7	**15**	1070.2
16	525.4	9.6	**16**	1081.8
17	948.5	9.5	**17**	1127.3
18	1127.3	9.7	**18**	1135.3
19	1135.3	9.7	**19**	1206.5
20	1386.0	12.8	**20**	1386.0
Average	929.2		**Percentile**	
StdDev Population	201.0		**35**	850.8
Min	525.4		**50**	937.6
Max	1386.0		**90**	1135.3
Range	860.6		**95**	1206.5

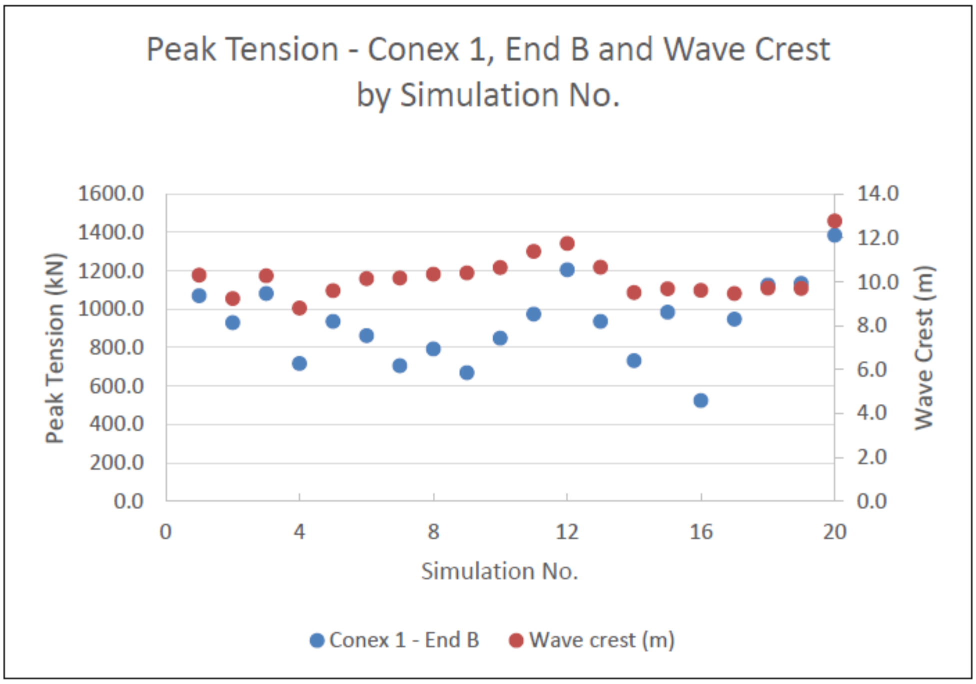


FIGURE. 3-2 20 SEED - PEAK TENSIONS

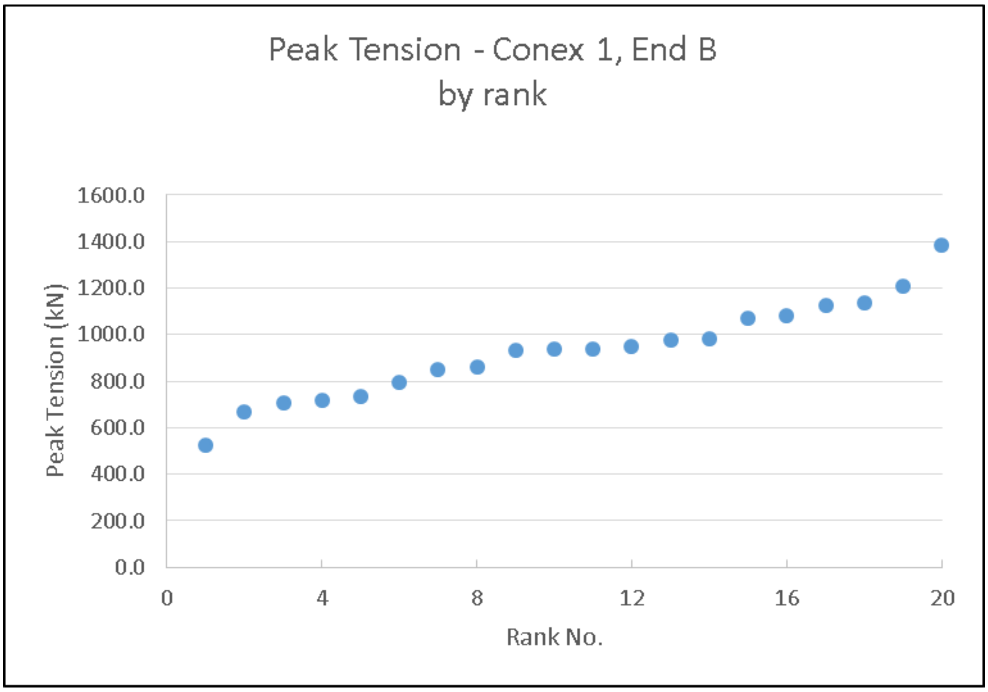


FIGURE. 3-3 20 SEED – RANK ORDERING

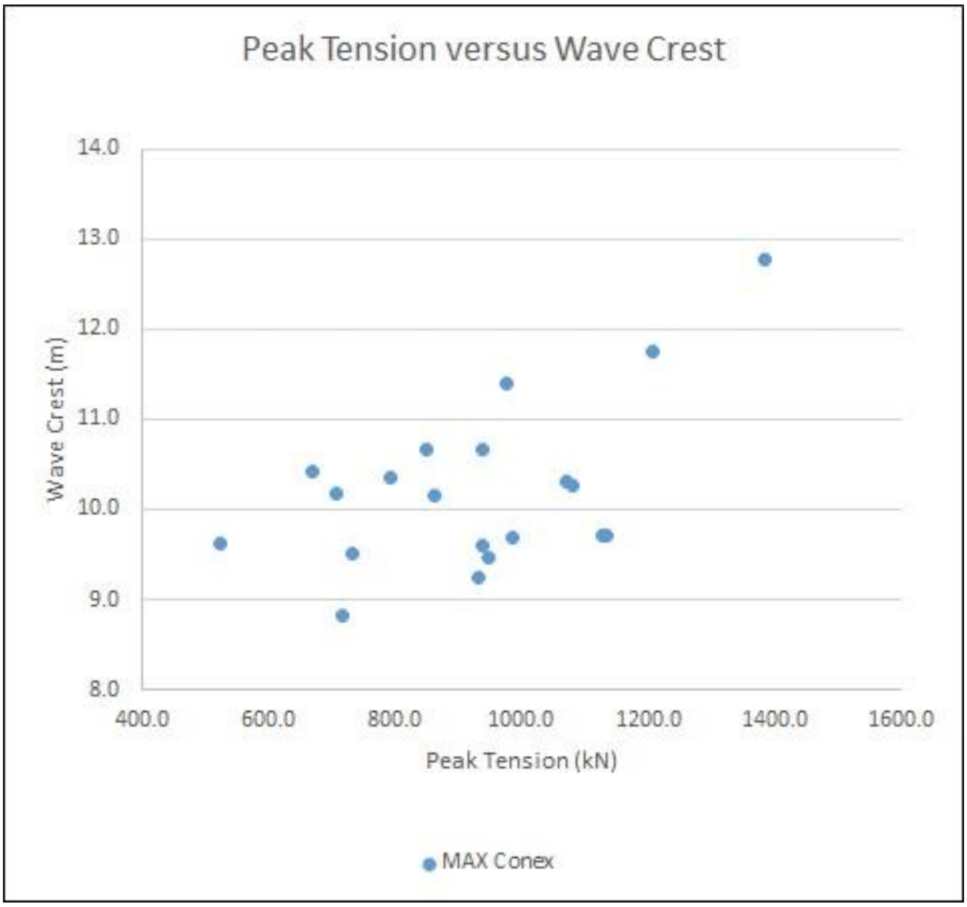


FIGURE. 3-4 PEAK TENSION VERSUS WAVE CREST

3.1.7 LONG RUN SIMULATION – 10,800 SEC

Long Run analyses were attempted for 10,800sec simulation using "End Orientation model no Nodo", seed 174813152 (original). In fact, these simulations took so long that tests a) and c) were manually terminated at around 5890sec.

a. End Orientation model no Nodo
b. End Orientation model no Nodo – Half Elements
c. End Orientation model no Nodo with Wing
d. End Orientation model no Nodo with Wing – Half Elements

TABLE. 3-6 LONG RUN ANALYSES

Model	Tension (kN) Cadena 1 End A	Conex 1 End B	Run length (sec)	Time of peak (sec)
End Orientation no Nodo	1093.7	1085.1	5897*	2,139
End Orientation no Nodo - Half Elements	1081.4	1071.6	10,800	4,035
End Orientation no Nodo - Wing	1085.6	1079.0	5890*	2,530
End Orientation no Nodo - Wing - Half Elements	1136.8	1130.4	10,800	10,671

** manually terminated due to excessive run time*

Event	Value (m)	Global Time (s)
Largest Rise	18.06	8961.19
Largest Fall	17.30	3742.59
Highest Crest	9.36	3742.59
Lowest Trough	-10.48	8961.19

Although each simulation had a peak crest event at 3,742sec, none of them demonstrated largest peak tension events near this time.

Also, all the peak tensions were larger than the basis values (941.3kN for Cadena 1 End A, and 936.8kN for Conex 1 End B), see Table. 3-4 above.

This indicates that the assumption of peak tension occurring with peak wave crest is not well founded. A clearer understanding of the relationship between WEC motion/offset response to tension is required prior to committing to peak tension design tension.

3.1.8 TIME STEP SENSITIVITY

Implicit time step sensitivity tests were done, using 5600s duration and "End Orientation model no Nodo", seed 174813152 (original) for the following time steps: 0.003s, 0.006s, 0.012s, 0.024s, 0.048s, 0.096s, 0.192s, 0.384s, 0.768s.

TABLE. 3-7 TIME STEP SENSITIVITY

Times step (sec)	Tension (kN)	Time (sec)
0.0015	1085.1	2139
0.003	956.6	3744
0.006	1063	4035
0.012	1067.99	4035
0.024	968.4	4308
0.048	1069.3	4035
0.096	FAIL	-
0.192	FAIL	-
0.384	FAIL	-
0.768	FAIL	-

The purpose of this test was to test the sensitivity/convergence to time step and peak tension prediction, with a potential view to having faster 3-hour simulations by using larger time steps.

However, there is not a consistent time event when peak tension occurs. Also, the magnitude of the peak tension varies by more than 130kN. Again, this indicates that the assumption of peak tension occurring with peak wave crest is not well founded; and that a clearer understanding of the relationship between WEC motion/offset response to tension is required prior to committing to peak tension design tension.

3.1.9 ELEMENT DENSITY SENSITIVITY

A sensitivity study was done on the element density on the mooring lines, using the "End Orientation model no Nodo", across a range of simulation lengths: 200s, 400s, 800s, 1600s duration with, with seed 174813152 (original). The element density as a factor of the basis model was:

a. Half elements
b. 1x element
c. 2x elements
d. 4x elements

TABLE. 3-8 ELEMENT DENSITY SENSITIVITY

Cadena 1 End A	Factor on Number of Elements			
Duration (sec)	**0.5**	**1**	**2**	**4**
200s duration	942.7	**941.3**	941.6	943.4
400s duration	982.6	977.2	980.6	987.4
800s duration	981.4	968.7	997.0	956.6
1600s duration	955.6	918.0	957.5	967.5

Conex 1 End B	Factor on Number of Elements			
Duration (sec)	**0.5**	**1**	**2**	**4**
200s duration	938.3	**936.8**	937.1	939.0
400s duration	978.5	968.7	976.5	983.2
800s duration	977.3	964.3	992.8	952.4
1600s duration	951.3	910.7	953.1	963.3

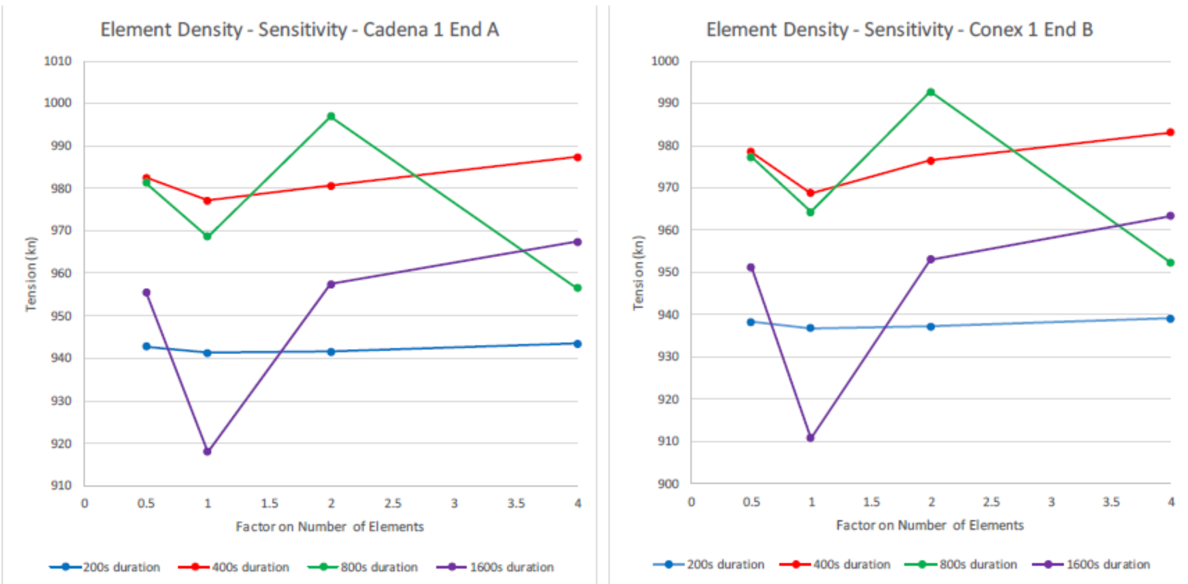


FIGURE. 3-5. ELEMENT DENSITY SENSITIVITY

The purpose of this test was to investigate the sensitivity/convergence to element size/number in the mooring lines.

However, this showed little or no consistent convergence with increased number of elements and no-uniform relationship with simulation length. Again, this indicates that better 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.

3.1.10 **OUTCOMES**

As a result of the broad range of sensitivity analyses performed on the moored WEC device for Phase 1, the following points are noted:

- Model modification - the modified model "End Orientation" demonstrated that it gave the same peak tension as the Original model. However, it was surprising that variation was observed by removal of the Nodo (3D buoy element), that were used to connect the catenary line elements.
- Start Time – 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. This raised the question: *Is the short simulation length (200sec) appropriate?*
- Number of wavelets sensitivity - these tests are 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, it did illustrate the fact that larger crest events can occur by varying the number of wavelets. This raised the questions: *Are simulations base on 100 wavelets appropriate?*
- Cd and Ca sensitivity – the 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 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. Also the correlation between peak wave crest and peak tension is poor.
- Long Run Simulation or 10,800sec – although each simulation had a peak crest event at 3,742sec, none of them demonstrated largest peak tension events near this time. Also the peak tensions that were predicted were much larger than those occurring around the peak wave crest. This indicates that the assumption of peak tension occurring with peak wave crest is not well founded.

- 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.

A better 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.

3.2 DIVERGENCE OF RESPONSE IN A MOORED WEC

This report investigates the variation in WEC and mooring response based on the numerical models. The variation in responses was raised in the Ref. [1], wherein it was observed that mooring line tension responses and WEC motions were very sensitive to number of elements in the mooring line and size of time step.

The report uses irregular and regular wave tests to investigate the source of the divergence of WEC response. From these investigations it was observed that the simulations that vary by time step or element density, have near identical motion and tension responses for the early part of the simulation. Thereafter simulations vary as a consequence of the MARMOK model's sensitivity to various parameters within the model.

3.2.1 VARIATION IN MOORING RESPONSE

A matrix of 3-hour simulations was analysed of the moored WEC, wherein both the element density on the mooring lines and time step of the solution algorithm were varied. The variations included:

- Mooring line element density - Half Element, 1.0 x Element, 2.0 x Element and 4.0 x Element
- Time step variation – 0.0015s, 0.003s, 0.006s, 0.012s, 0.024s, 0.048s

It was observed that the peak tension in the mooring lines varied from simulation to simulation without indicating that convergence was going to be achieved via either increased element density on the mooring lines, or reduction in the time step. The time event when peak tension occurred also varied from simulation to simulation.

Table. 3-9 and

Table. 3-10 presents the maximum observed effective tension of Conex1 and associated time event when these occurred.

TABLE. 3-9 CONEX1 PEAK TENSION

Time Steps (s)	0.5 x Element	1.0 x Element	2.0 x Element	4.0 x Element
0.0015	1071.6	1085.1	1065.9	1053.2
0.003	1034.8	1115.3	1060.2	1091.5
0.006	1095.2	1047.0	1071.1	1116.1
0.012	994.9	1065.6	1055.3	-
0.024	1059.8	1048.7	1077.2	-
0.048	1077.1	1109.8	-	-

TABLE. 3-10 TIME EVENT OF CONEX1 PEAK TENSION OCCURENCE

Time Steps (s)	0.5 x Element	1.0 x Element	2.0 x Element	4.0 x Element
0.0015	4035.0	2139.3	4035.0	2139.3
0.003	7119.7	7000.0	6283.6	188.4
0.006	10670.6	7119.9	4034.8	4034.8
0.012	5992.1	4035.1	7120.1	-
0.024	4034.6	7012.2	10670.8	-
0.048	4035.0	7000.4	-	-

TABLE. 3-11 TIME EVENT OF CONEX1 PEAK TENSION OCCURRENCE

Time Steps (s)	0.5 x Element	1.0 x Element	2.0 x Element	4.0 x Element
0.0015	1049.7	1043.1	1050.3	1010.3
0.003	992.3	1081.7	1050.2	1056.1
0.006	1054.8	1013.2	1036.4	1077.4
0.012	980.6	1023.5	1007.7	-
0.024	1049.2	1005.2	1051.3	-
0.048	1029.6	1067.0	-	-

Additionally the predicted extreme mooring tension as evaluated using the 'Generalised Pareto' method, using the peak tension history within each simulation. Using this method, the maximum predicted Conex1 tension for a 3-hour storm duration are presented Table. 3-12 for the matrix of test cases. Again it is observed that the peak tension predictions vary.

TABLE. 3-12 MAXIMUM ESTIMATED CONEX1 TENSION IN 3-HOURS STORM

Time Steps (s)	0.5 x Element	1.0 x Element	2.0 x Element	4.0 x Element
0.0015	1049.7	1043.1	1050.3	1010.3
0.003	992.3	1081.7	1050.2	1056.1
0.006	1054.8	1013.2	1036.4	1077.4

3.2.2 IRREGULAR WAVE TEST

The early response of the moored WEC, i.e. within the first 400sec of the simulation, was investigated by doing the following two sets of tests:

1. Wave elevation check using a common static point in space (x: 131.535m, y: 1.25m, z:0m). This static point is approximately in the locality of the WEC.

2. Surge excursion check at the geometric centre of the WEC (x: 0.0m, y: 0.0m, z:17.77m), which is at the same elevation of the Conex End-B.

These two checks were compared for the following:

a) Mooring line element densities: Half Element, 1.0 x Element, 2.0 x Element and 4.0 x Element.

b) Time steps of 0.0015s, 0.003s, 0.006s, 0.012s, 0.024s and 0.048s

Wave elevation and surge excursion time traces were captured for the first 400s of a 3-hour simulation. The wave elevations are presented in Figure. 3-6 to Figure. 3-11 and the surge excursion time traces are presented in Figure 3-7 to Figure 3-12 on a per Time Step basis.

From the **Wave Elevation** graphs (Figure. 3-6 to Figure. 3-11) the following point can be made: **Wave elevation** at the static point is the same for all time steps between 0.0015s to 0.048s, for all mesh densities.

NB: The simulation for mesh density 4.0 x Element terminated prematurely for the step 0.024s at 200sec, and failed to run for time the 0.048s time step.

From the **Surge Excursion** curves are presented on a **by Time Step basis** (Figure. 3-12 to Figure. 3-17), it is seen that divergence between the various simulations can occur at any point e.g. after the first 10sec to 200sec. There does not appear to be any sustained pattern of when the divergence occurs with regard to Element Density and Time Step combinations.

The same **Surge Excursion** curves are presented on a **by Element Density basis** in Figure. 3-18 to 3-21. These show that less refined element density (Half Element and 1 x Element) appear to be more stable and diverge less than the more refined element densities (2 x Element and 4 x Element).

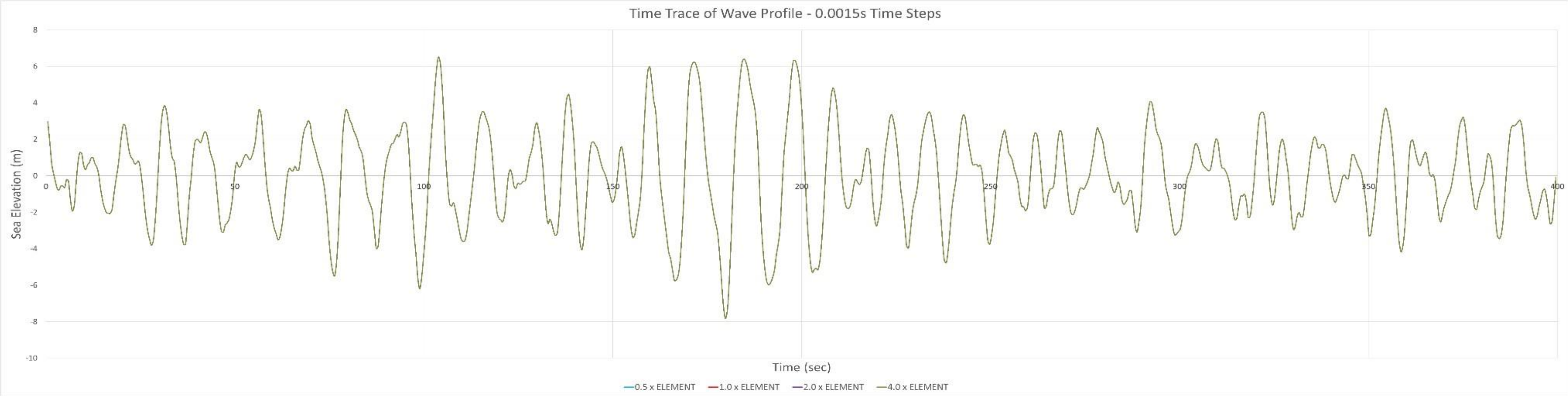


FIGURE. 3-6 WAVE ELEVATION TIME TRACE 0.0015S TIME STEPS

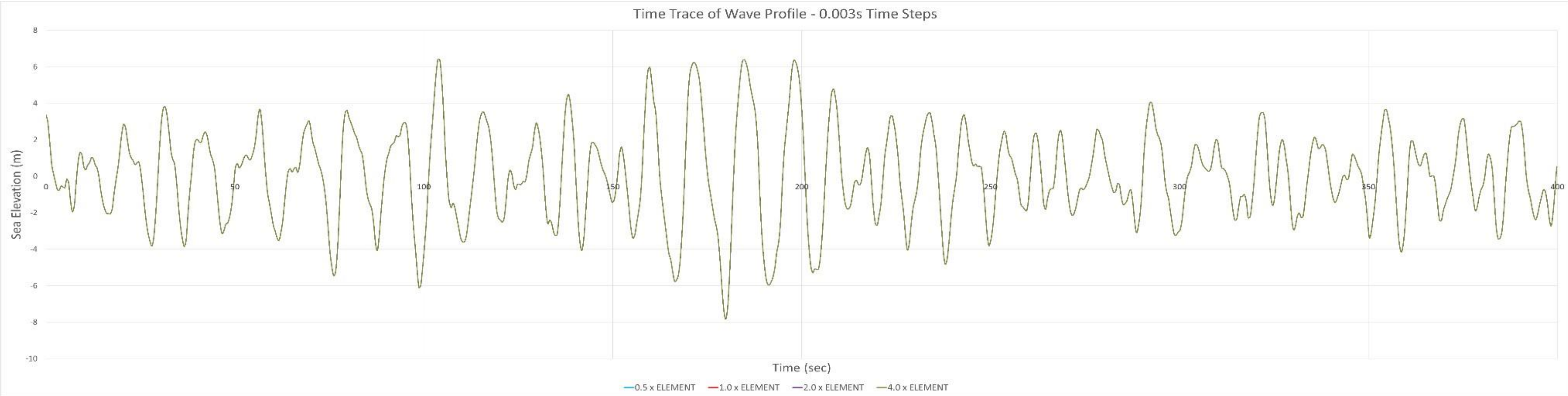


FIGURE. 3-7 WAVE ELEVATION TIME TRACE 0.003S TIME STEPS

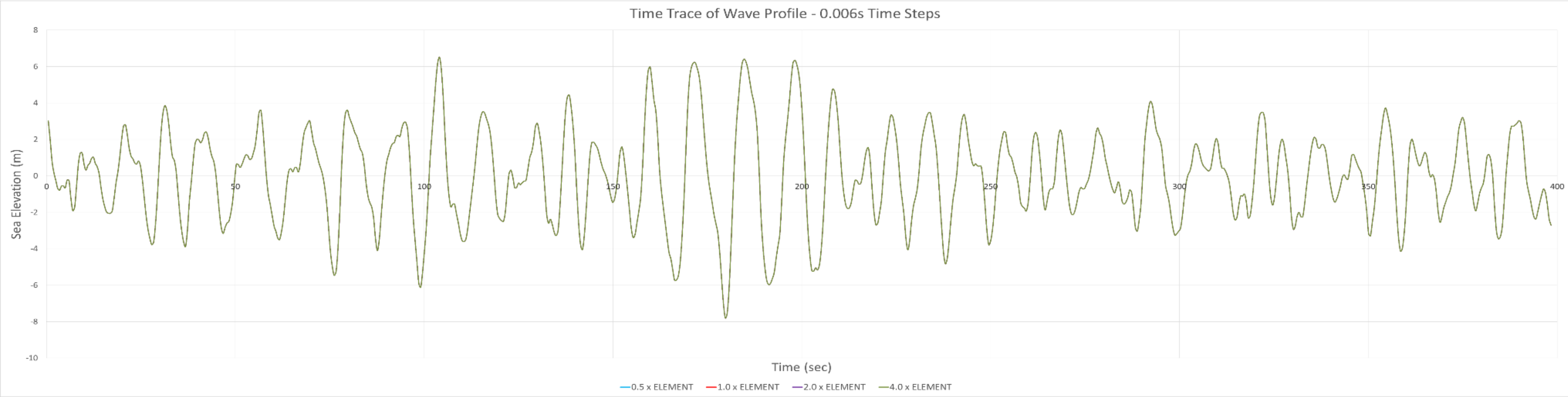


FIGURE. 3-8 WAVE ELEVATION TIME TRACE 0.006S TIME STEPS

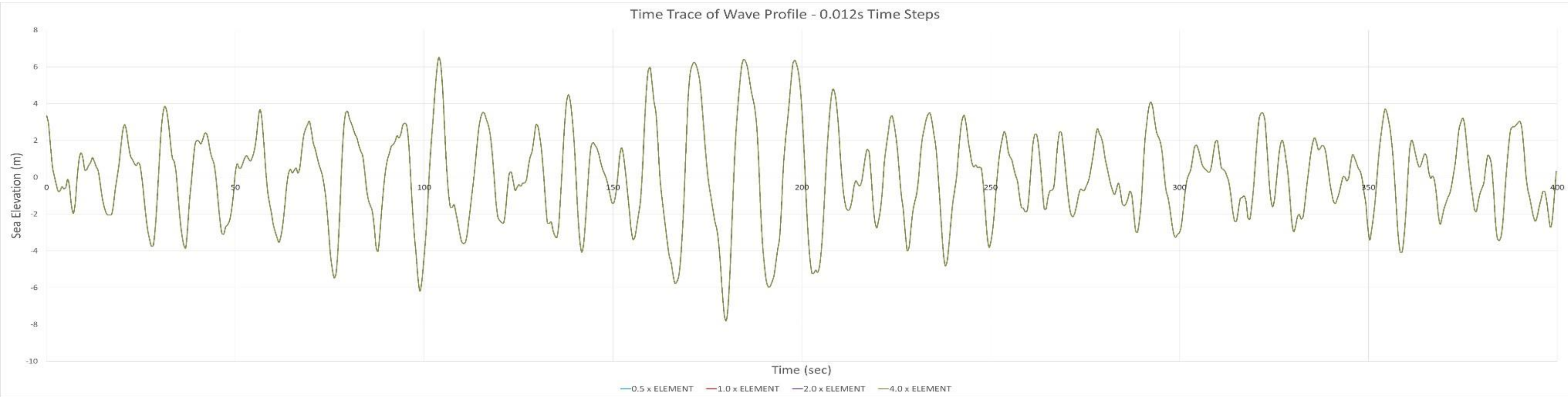


FIGURE. 3-9 WAVE ELEVATION TIME TRACE 0.012S TIME STEPS

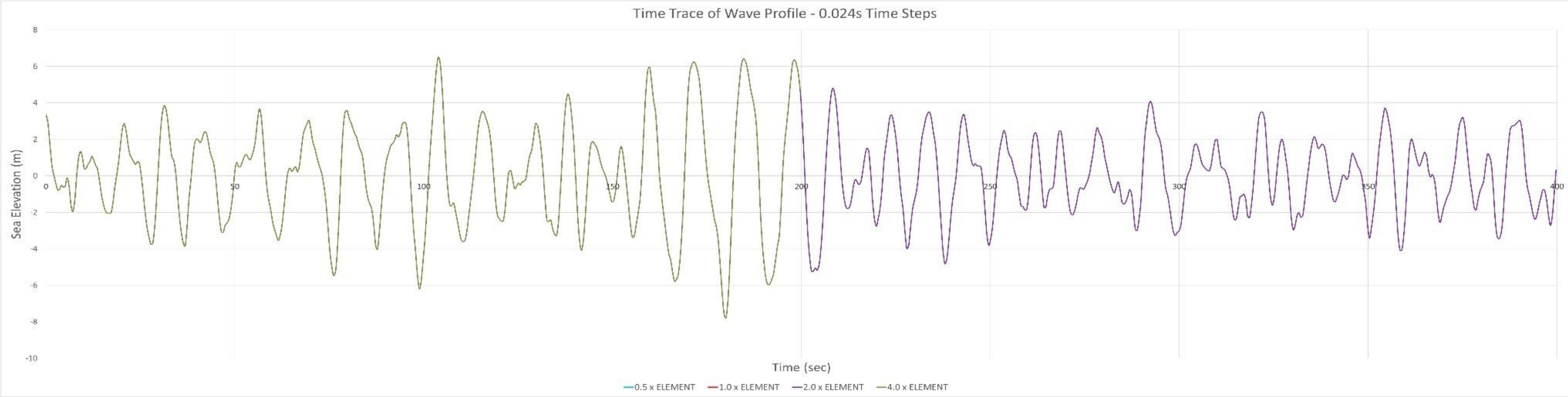


FIGURE. 3-10 WAVE ELEVATION TIME TRACE 0.024S TIME STEPS (NB. 4 X ELEMENT TERMINATED AT APPROXIMATELY 200S)

FIGURE. 3-11 WAVE ELEVATION TIME TRACE 0.048S TIME STEPS (NB. 4 X ELEMENT FAILED TO EVALUATE)

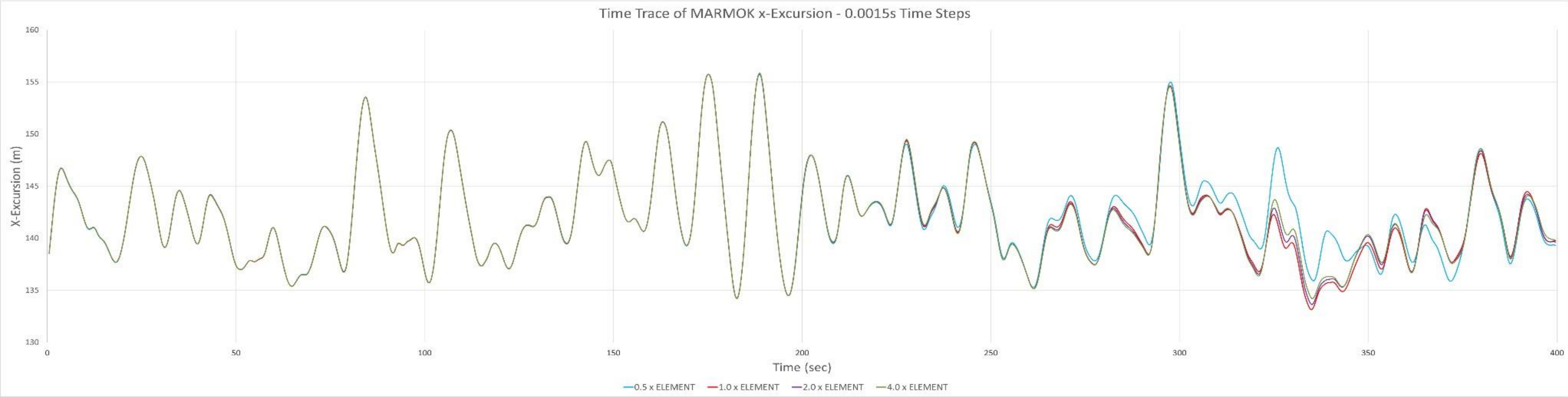


FIGURE. 3-12 WEC SURGE EXCURSION TIME TRACE 0.0015S TIME STEPS

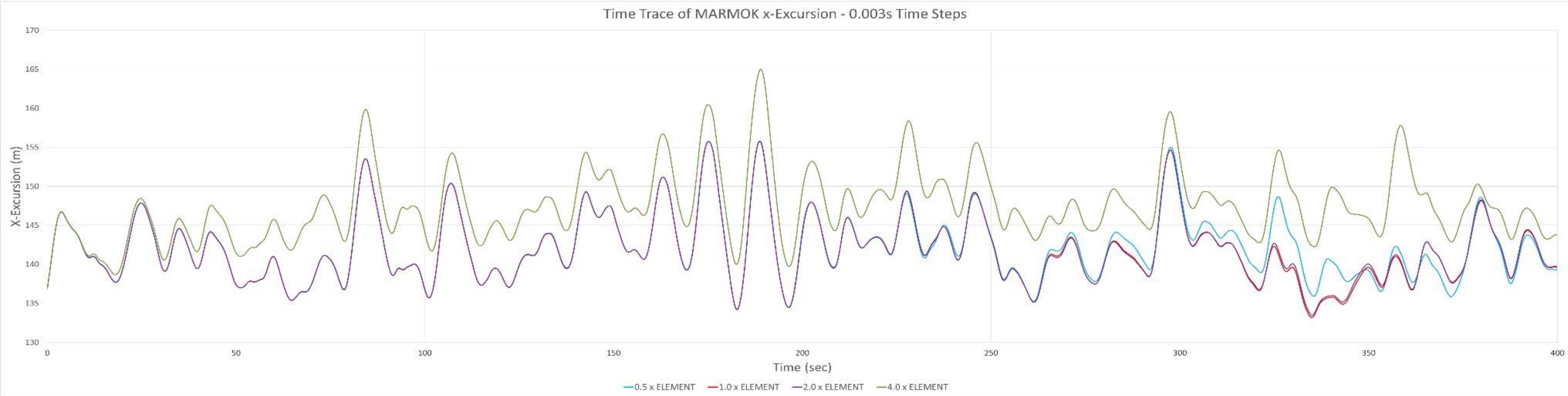


FIGURE. 3-13 WEC SURGE EXCURSION TIME TRACE 0.003S TIME STEPS

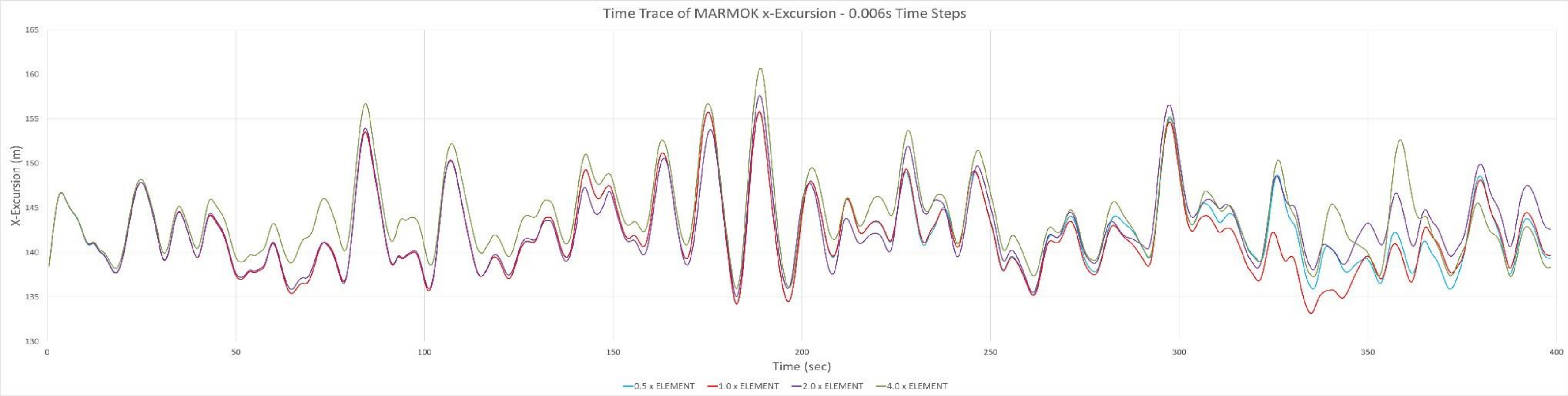


FIGURE. 3-14 WEC SURGE EXCURSION TIME TRACE 0.006S TIME STEPS

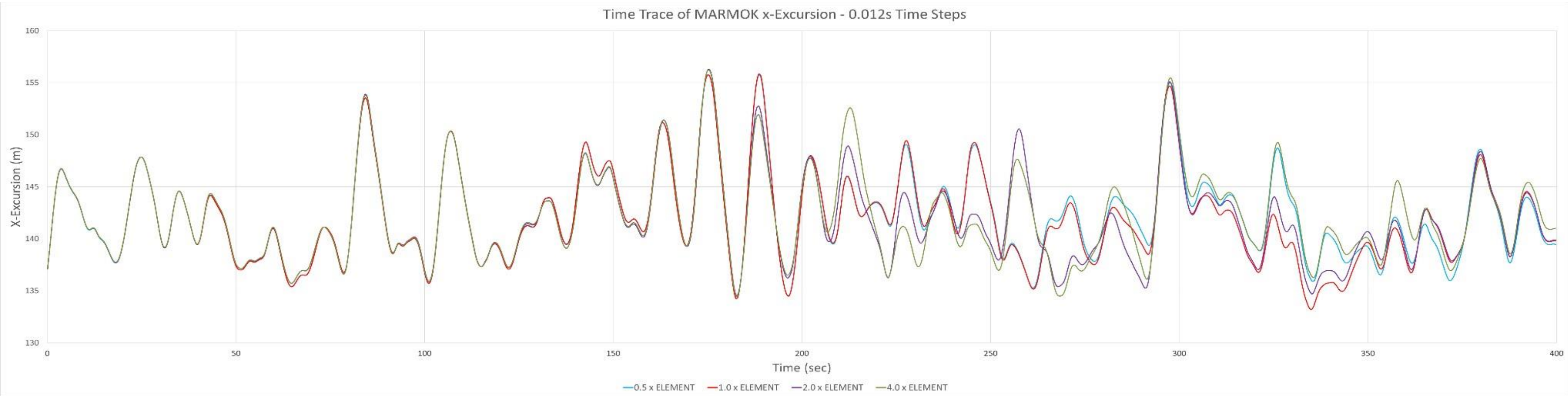


FIGURE. 3-15 WEC SURGE EXCURSION TIME TRACE 0.012S TIME STEPS

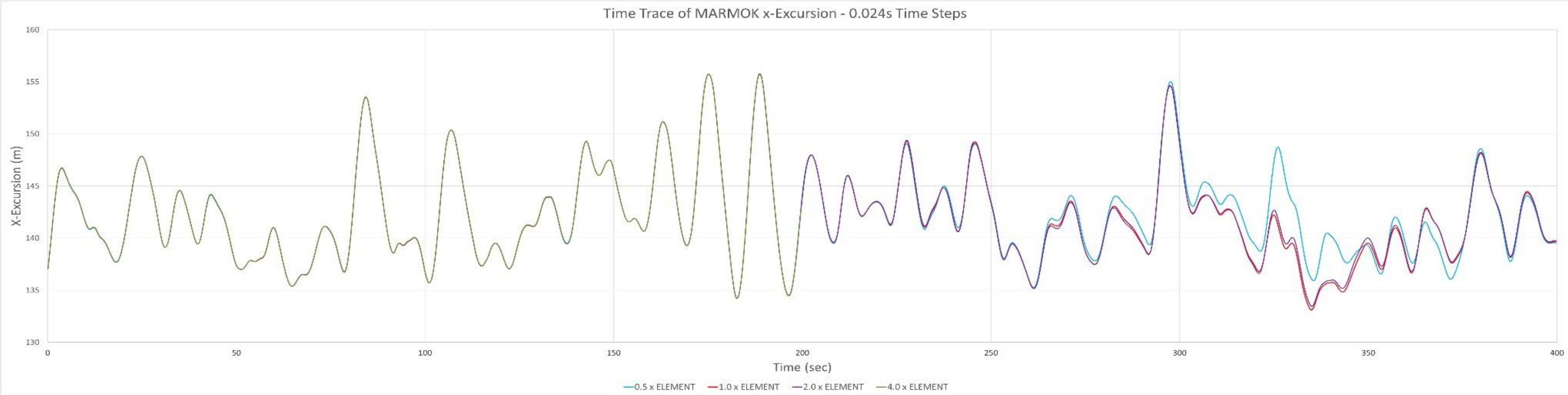


FIGURE. 3-16 WEC SURGE EXCURSION TIME TRACE 0.024S TIME STEPS

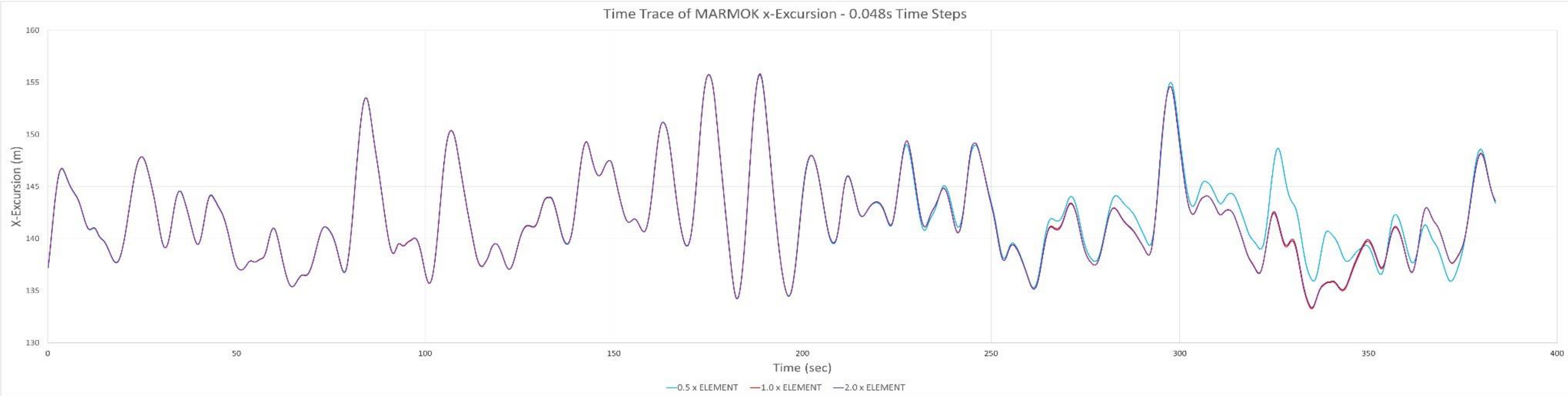


FIGURE. 3-17 WEC SURGE EXCURSION TIME TRACE 0.048S TIME STEPS

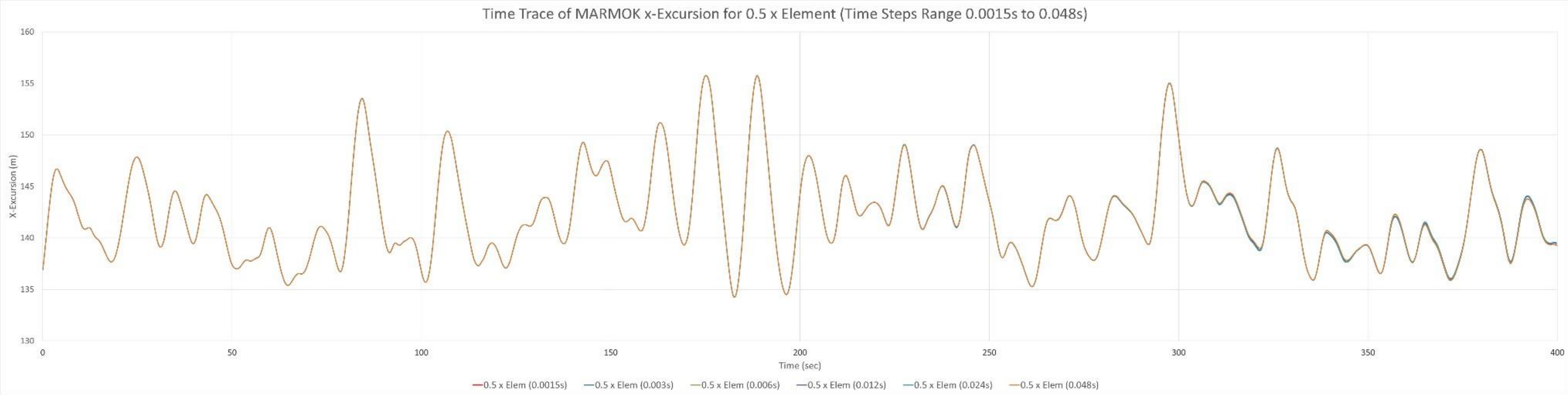


FIGURE. 3-18 COMPARISON OF WEC SURGE EXCURSION TIME TRACE IN IRREGULAR WAVE FOR 0.5 X ELEMENT

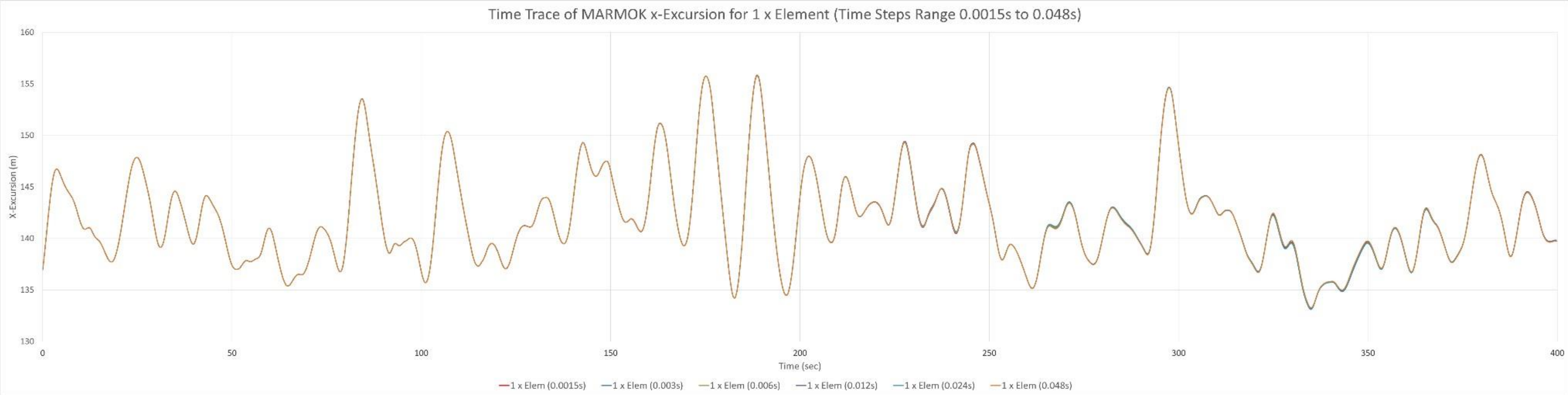


FIGURE. 3-19 COMPARISON OF WEC SURGE EXCURSION TIME TRACE IN IRREGULAR WAVE FOR 1 X ELEMENT

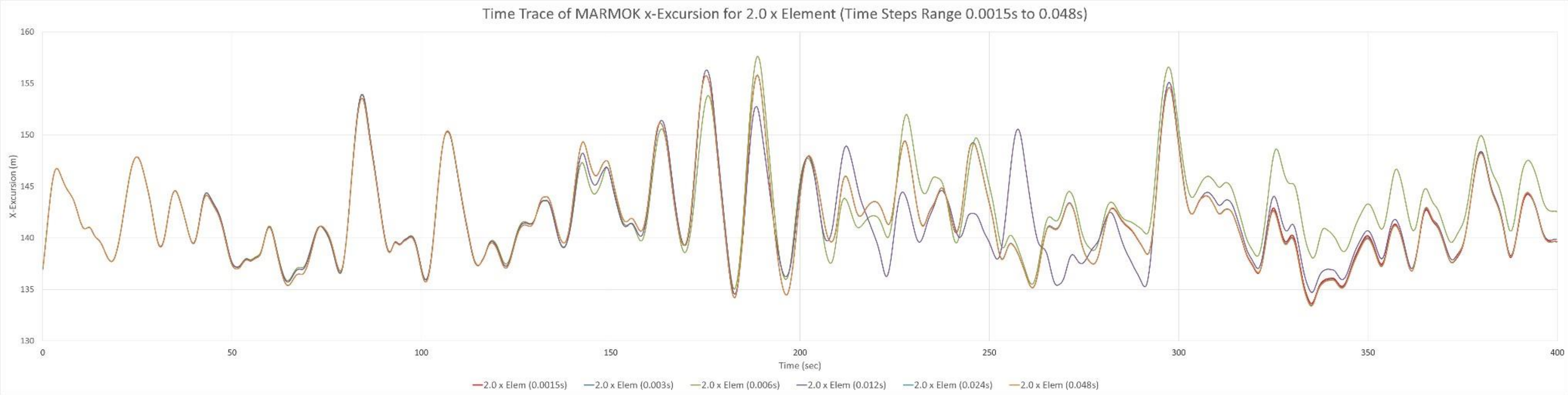


FIGURE. 3-20 COMPARISON OF WEC SURGE EXCURSION TIME TRACE IN IRREGULAR WAVE FOR 2 X ELEMENT

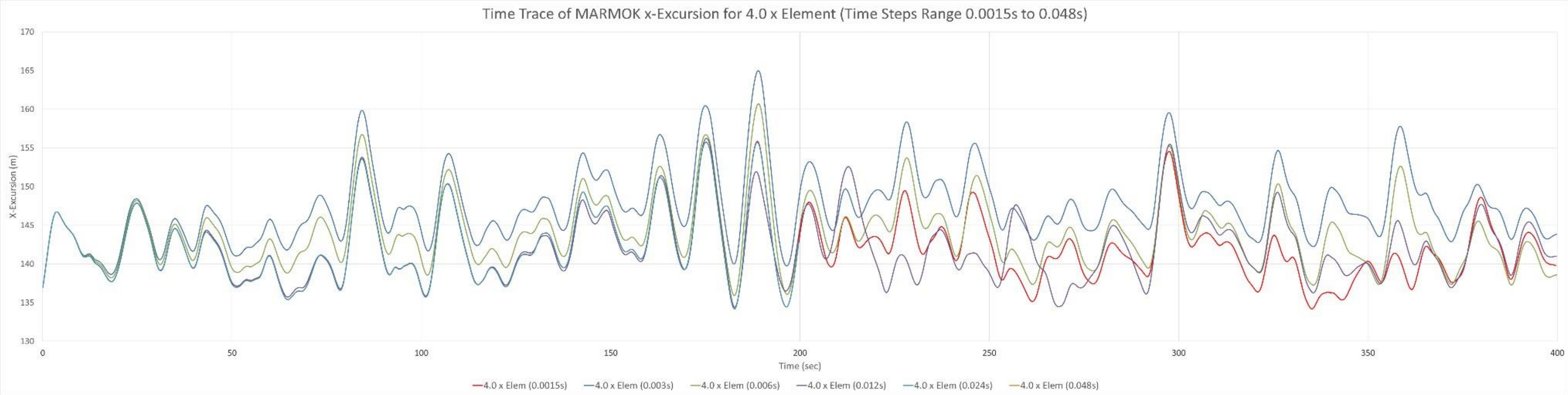


FIGURE. 3 21 COMPARISON OF WEC SURGE EXCURSION TIME TRACE IN IRREGULAR WAVE FOR 4 X ELEMENT

3.2.3 REGULAR WAVE TEST

In light of the tests done using Irregular seas in previous Section 3.2.2, some additional investigations were done using Regular waves to see if the divergence in Surge Excursion would occur in Regular waves as well. These Regular wave tests were done for:

- Mooring line element densities: Half Element, 1.0 x Element, 2.0 x Element and 4.0 x Element.
- Time steps: 0.0015sec and 0.006sec
- Wave Height =19.9m
- Wave period = 10.0sec and 15.0sec

Airy wave profile was used, and the simulation lengths were 400sec.

The wave elevations are presented in Figure. 3-21 to Figure. 3-24 and the surge excursion time traces are presented in Figure. 3-25 to Figure 3-33.

From the **Wave Elevation** graphs (Figure. 3-21 to Figure. 3-24) the following point can be made: **Wave elevation** at the static point is the same for all mesh densities, for both wave periods and time steps.

From the **Surge Excursion** graphs, it is seen that divergence occurs for 10sec wave period (Figure. 3-25 to Figure. 3-28) for the various element densities and time steps, but barely at all for the 15sec wave period. For the 15sec wave period (Figure. 3-29 to Figure. 3-33), the moored WEC responds in a much more consistent manner regardless of element densities and time steps.

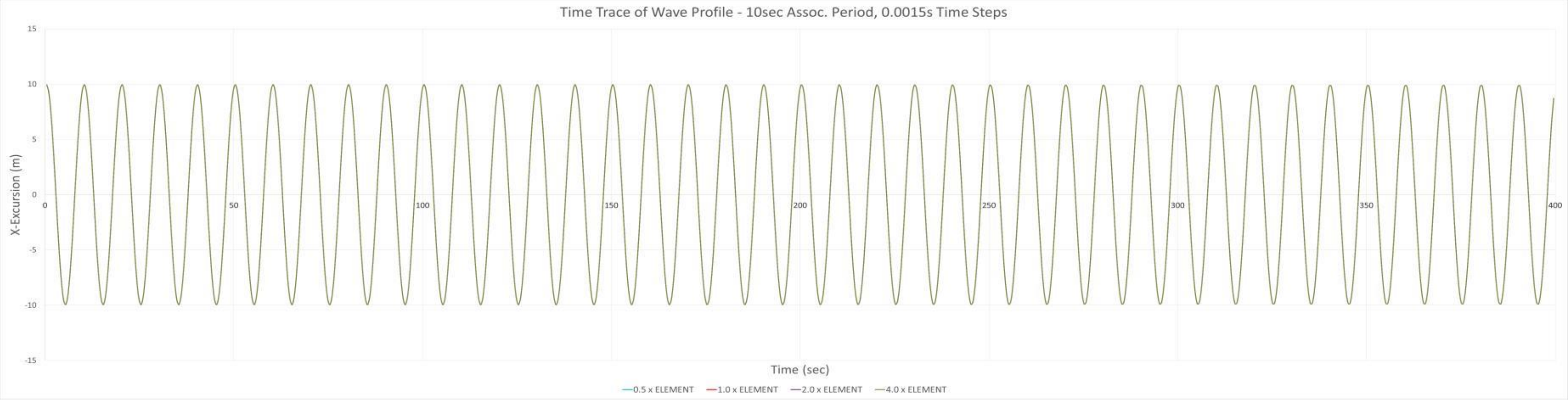


FIGURE. 3-21 WAVE ELEVATION TIME TRACE 0.0015S TIME STEPS (REGULAR WAVE, ASSOC. PERIOD 10S)

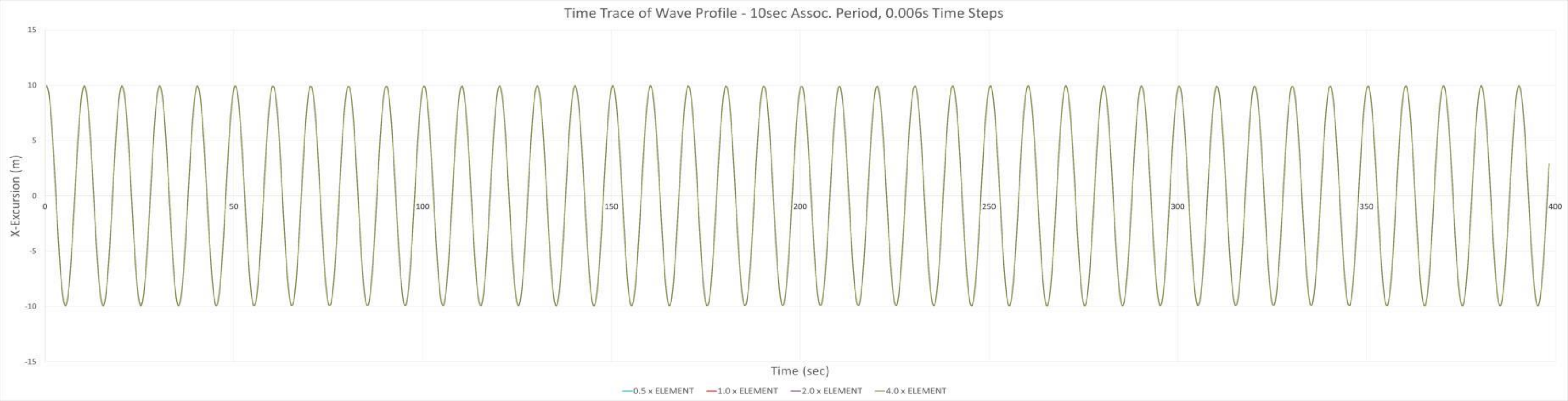


FIGURE. 3-22 WAVE ELEVATION TIME TRACE 0.006S TIME STEPS (REGULAR WAVE, ASSOC. PERIOD 10S)

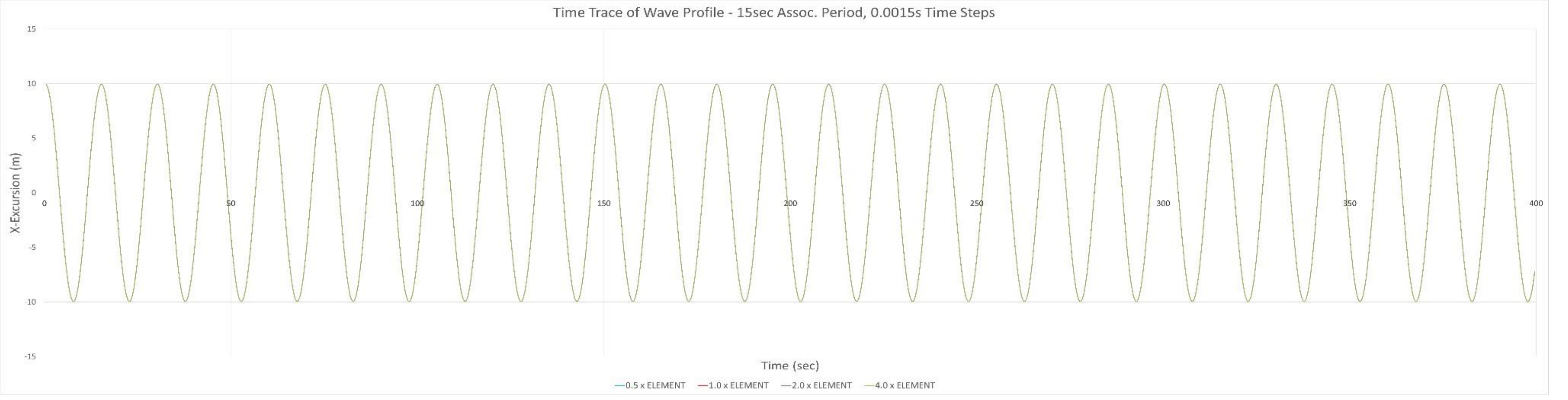


FIGURE. 3-23 WAVE ELEVATION TIME TRACE 0.0015S TIME STEPS (REGULAR WAVE, ASSOC. PERIOD 15S)

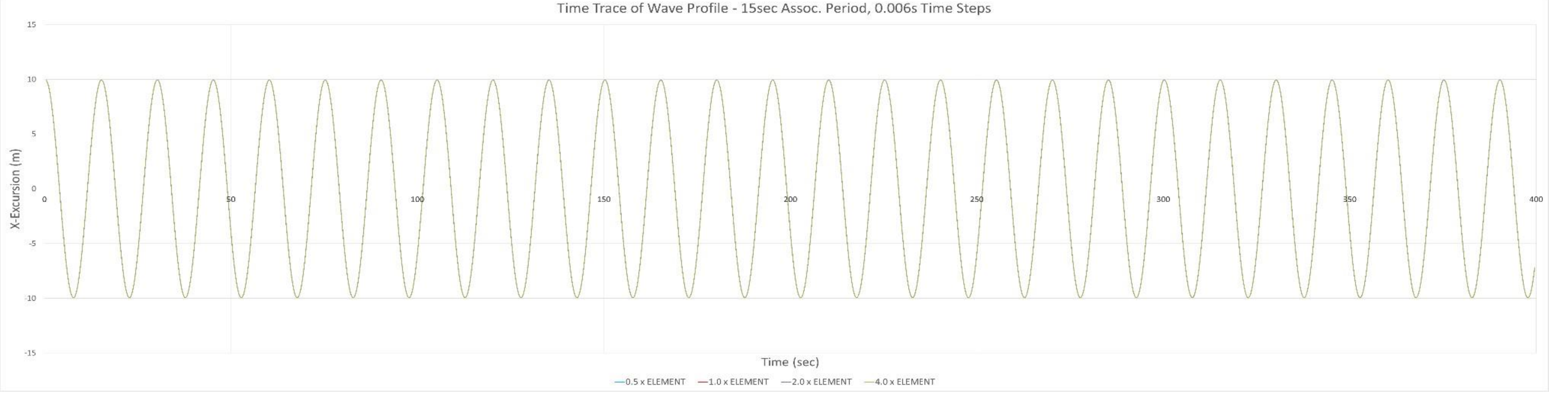


FIGURE. 3-24 WAVE ELEVATION TIME TRACE 0.006S TIME STEPS (REGULAR WAVE, ASSOC. PERIOD 15S)

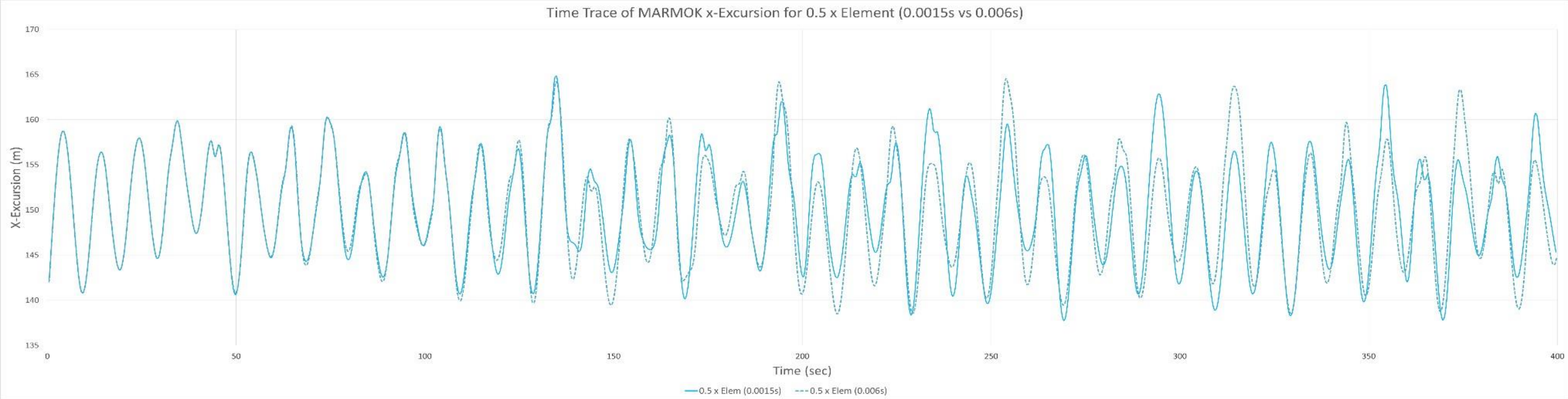


FIGURE. 3-25 COMPARISON OF WEC SURGE EXCURSION TIME TRACE IN REGULAR WAVE (ASSOC. PERIOD 10S) FOR 0.5 X ELEMENT

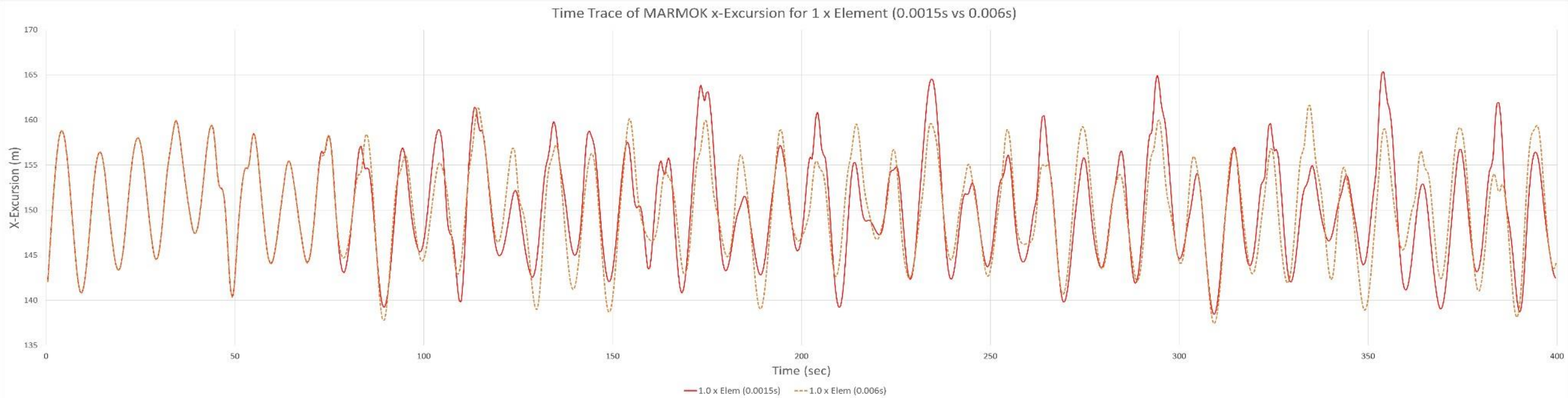


FIGURE. 3-26 COMPARISON OF WEC SURGE EXCURSION TIME TRACE IN REGULAR WAVE (ASSOC. PERIOD 10S) FOR 1 X ELEMENT

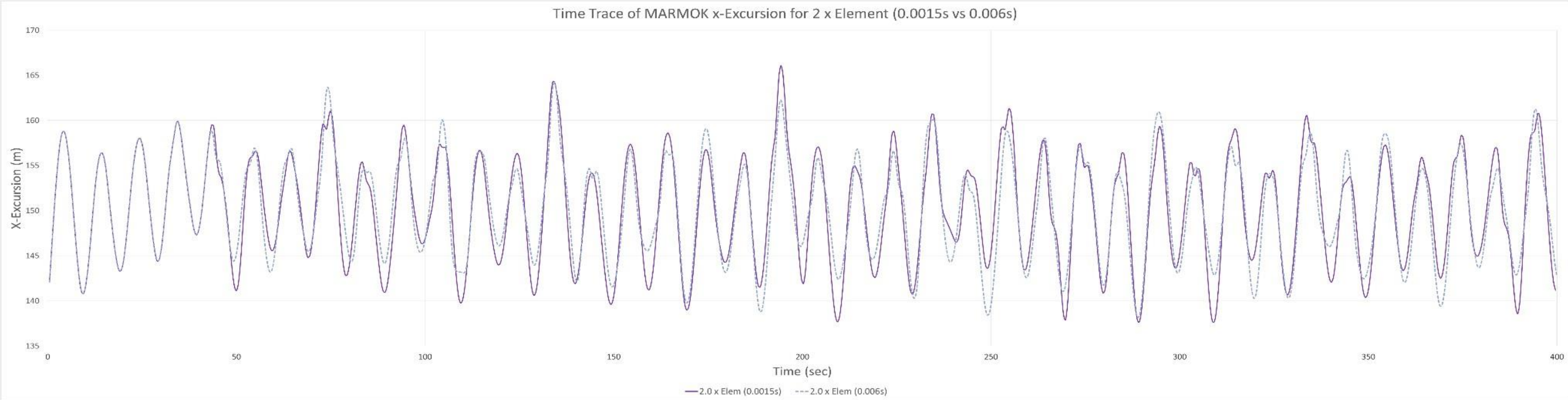


FIGURE. 3-27 COMPARISON OF WEC SURGE EXCURSION TIME TRACE IN REGULAR WAVE (ASSOC. PERIOD 10S) FOR 2 X ELEMENT

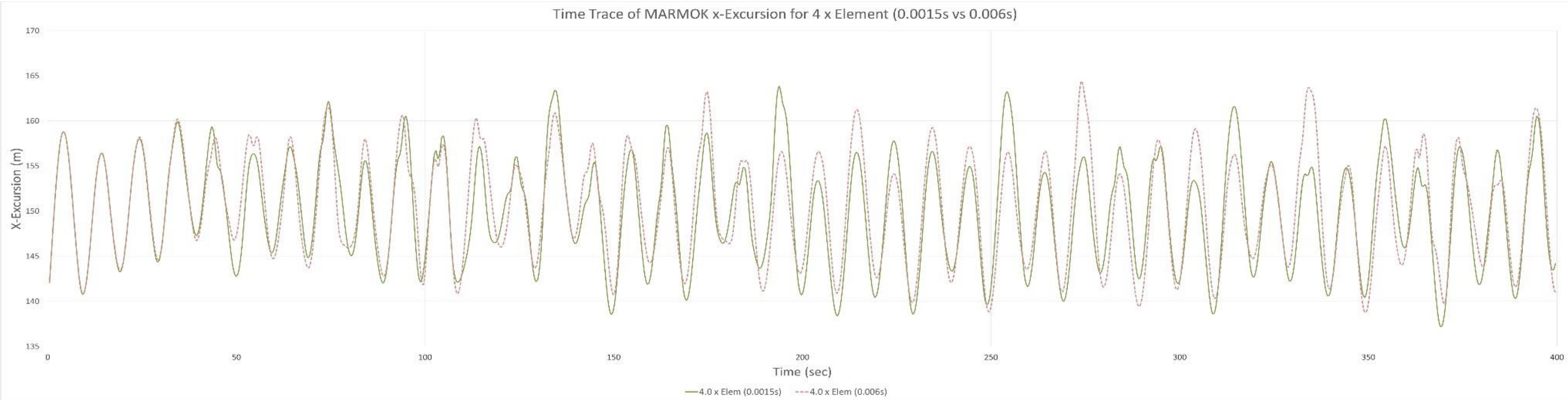


FIGURE. 3-28 COMPARISON OF WEC SURGE EXCURSION TIME TRACE IN REGULAR WAVE (ASSOC. PERIOD 10S) FOR 4 X ELEMENT

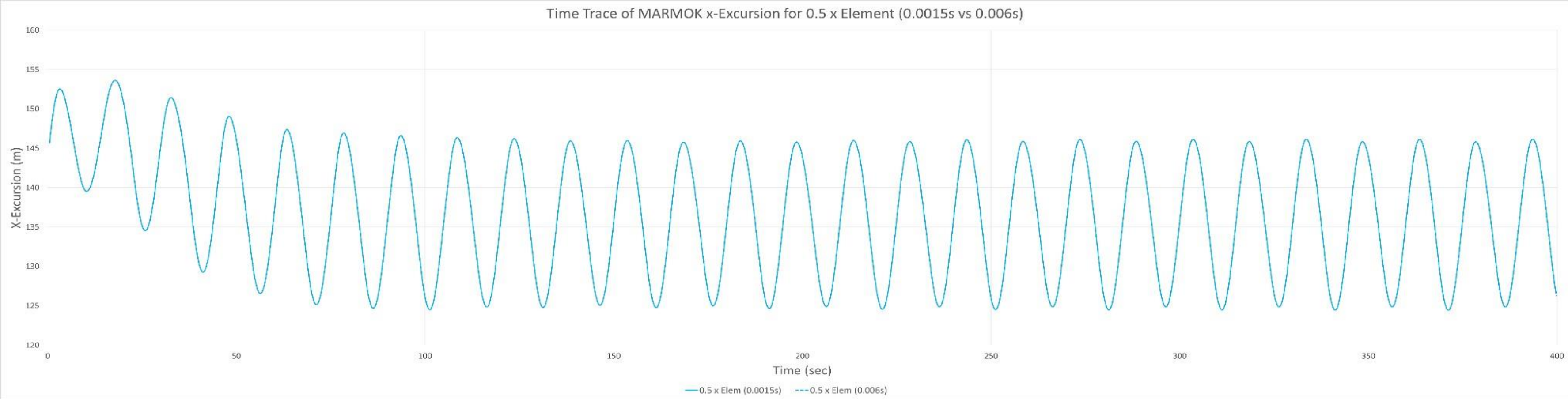


FIGURE. 3-29 COMPARISON OF WEC SURGE EXCURSION TIME TRACE IN REGULAR WAVE (ASSOC. PERIOD 15S) FOR 0.5 X ELEMENT

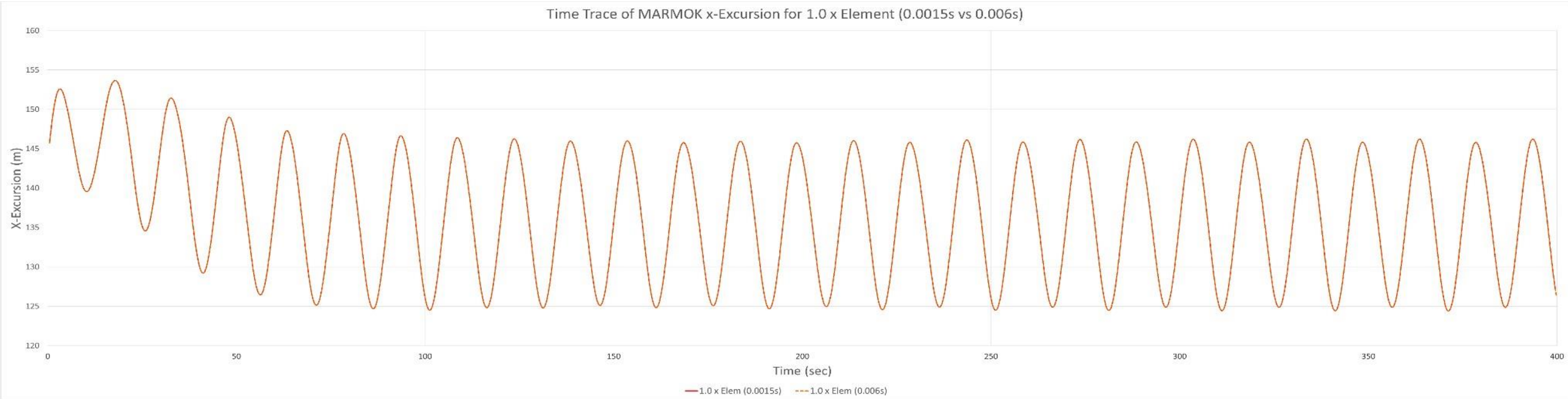


FIGURE. 3-30 COMPARISON OF WEC SURGE EXCURSION TIME TRACE IN REGULAR WAVE (ASSOC. PERIOD 15S) FOR 1 X ELEMENT

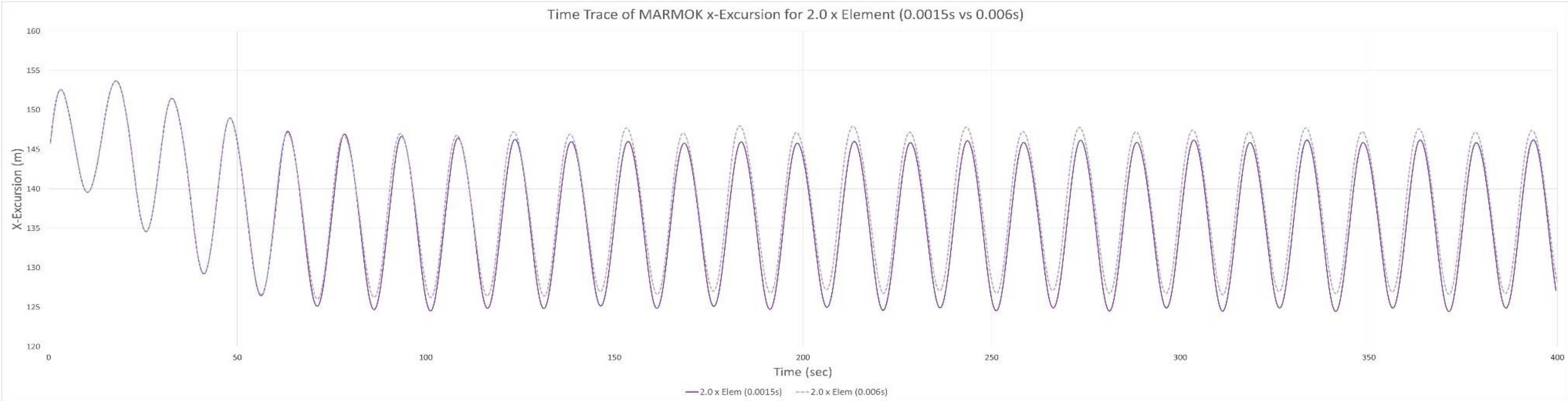


FIGURE. 3-31 COMPARISON OF WEC SURGE EXCURSION TIME TRACE IN REGULAR WAVE (ASSOC. PERIOD 15S) FOR 2 X ELEMENT

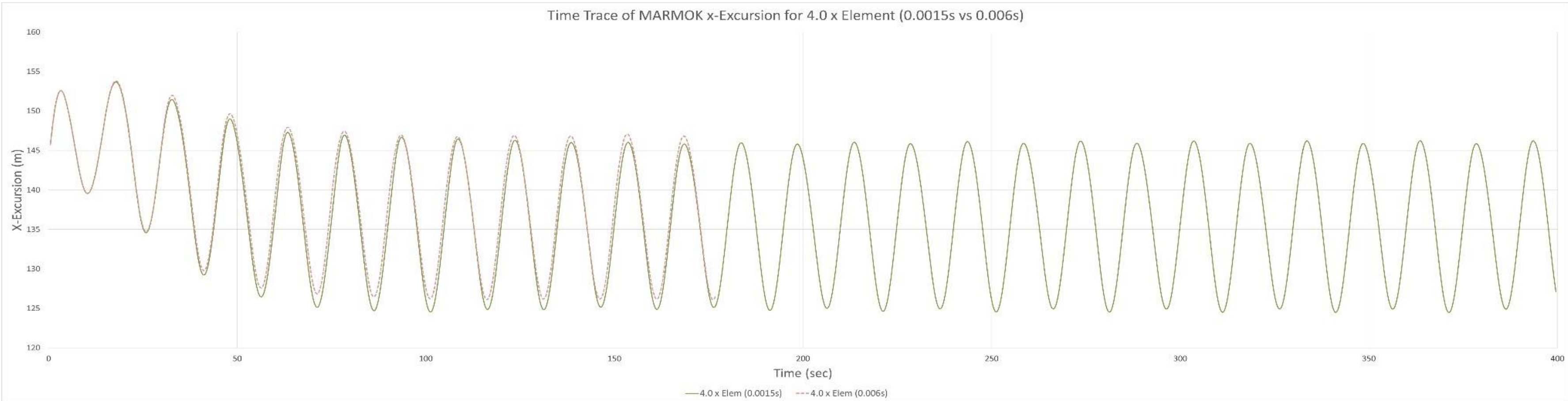


FIGURE. 3 33 COMPARISON OF WEC SURGE EXCURSION TIME TRACE IN REGULAR WAVE (ASSOC. PERIOD 15S) FOR 4 X ELEMENT (NB. 0.006S TIME STEP TERMINATED AT 177S)

3.2.4 SUMMARY OF WEC DIVERGENCE RESPONSE

Investigations in to the divergence of the WEC response for 400s allows the following conclusions to be drawn:

- It has been confirmed that the synthesis of the wave elevation is the same regardless of number of elements in the mooring line or the time step. This has been done for Regular and Irregular wave systems
- For Regular wave analyses, divergence of responses appears to be wave period dependent; in this instance shorter wave periods may observe divergence of results, whilst longer periods may not show divergence of results for different element densities and time steps.
- For Irregular wave analyses, less refined Element Density (Half Element and 1 x Element) appear to be more stable and diverge less than the more refined element densities (2 x Element and 4 x Element).
- For Irregular wave analyses, on a Time Step basis, it is seen that divergence between the various simulations can occur at any point e.g. after the first 10sec to 200sec. There does not appear to be any sustained pattern of when the divergence occurs with regard to Element Density and Time Step combinations.
- The cause for the divergence is most probably because the moored vessel response is sensitive to modifications in the model, which affect the response disproportionately.

3.3 YAW ROTATION REDUCTION OF A MOORED WEC

This section presents an investigation into the occurrence of large yaw rotations of the MARMOK WEC as observed in 3-hour mooring simulations. These large rotations are evidenced by yaw rotations of greater than 360deg. Furthermore, additional rotations compound to make these rotations increase to 720deg and 1080deg. Subsequently, large reverse rotations may occur.

The investigation illustrates that the following elements in the model, can all assist in reducing these excessively large rotations:

- Linear yaw damping
- Fairlead extension
- Elastic solid shapes

The following recommendations are made:

- Linear yaw damping – realistic values for the MARMOK should be identified

- Fairlead extension - the fairlead location should represent the actual outboard position
- Elastic solid shapes – these should be incorporated into future models.

The moored MARAMOK WEC is modelled in Orcaflex software. Details of the MARMOK, mooring system and basic responses are reported in Ref. [2] and [3]. From Ref. [3] it has been identified that the model of the MARMOK does not have any yaw damping directly from the WEC. Instead damping in the yaw direction comes only via the mooring lines.

From 3-hour time domain simulations it was observed that large yaw rotations occurred i.e. greater than 360deg. It is questionable that such large yaw rotations are realistic. Additionally, these very large yaw rotations imply that in general the MARAMOK is experiencing large rotations through its simulation and will be evidenced by large standard deviation of yaw.

3.3.1 LARGE YAW ROTATIONS

The basis model to demonstrate the presence of large Yaw rotations is *v3.7.2_EC1A_11.dat*, to which minor modifications have been made to make simpler definitions of the catenary leg and lay angles of the mooring components. This model has the original number of elements in the mooring lines and the time step for the Implicit Solver has been retained as 0.0015sec. This model was run for a 3-hour simulation length using the basis environment:

- Wind – Vw = 27.01m/s, NPD wind spectrum, Direction 34deg relative to model
- Wave – Hs = 10.7m, Tz = 9.2s, Gamma = 2.8, Direction 34deg relative to model
- Current - Vc at surface of 0.556m/s, Direction 34deg relative to model

Figure. 3-32 below presents the yaw rotation (Rotation 3, i.e. about the Z axis) during the simulation and Table. 3-13 presents the statistics of the Yaw rotation. It is clear that large (>360deg) rotations occur at random events throughout the simulation. Additionally, there are rotation reversals i.e. -360deg.

TABLE. 3-13 YAW (ROTATION 3) STATISTICS

	Yaw (deg)
Minimum	-73.0
Maximum	897.1
Mean	514.0
Std Dev	252.7

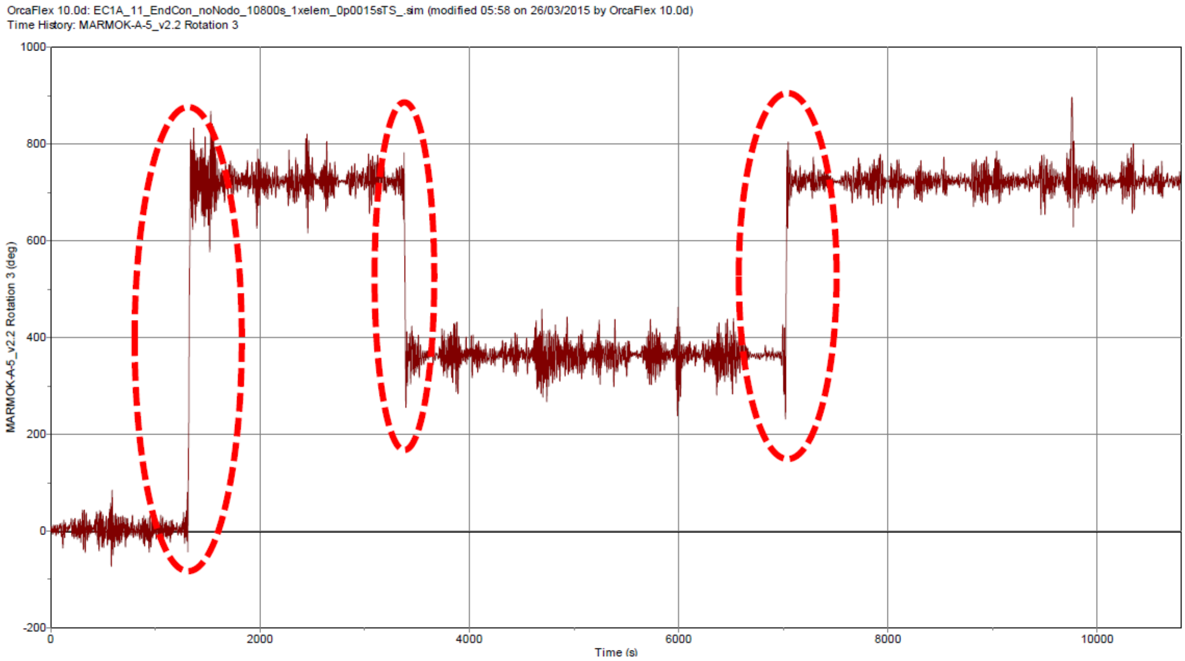


FIGURE. 3-32 WEC YAW (ROTATION 3) TIME TRACE PLOT (RED-DASHED ELLIPSE INDICATES LARGE ROTATIONS)

Zoomed-in detail of yaw rotation angles at the transition times (1335sec, 3394sec, 7035sec) are presented in Figure. 3-33 to Figure. 3-35. The associated time traces of the tension in Conex 1 End B are presented in Figure. 3-36 to Figure. 3-38. These show that when large rotation occurs, the mooring lines tension collapses.

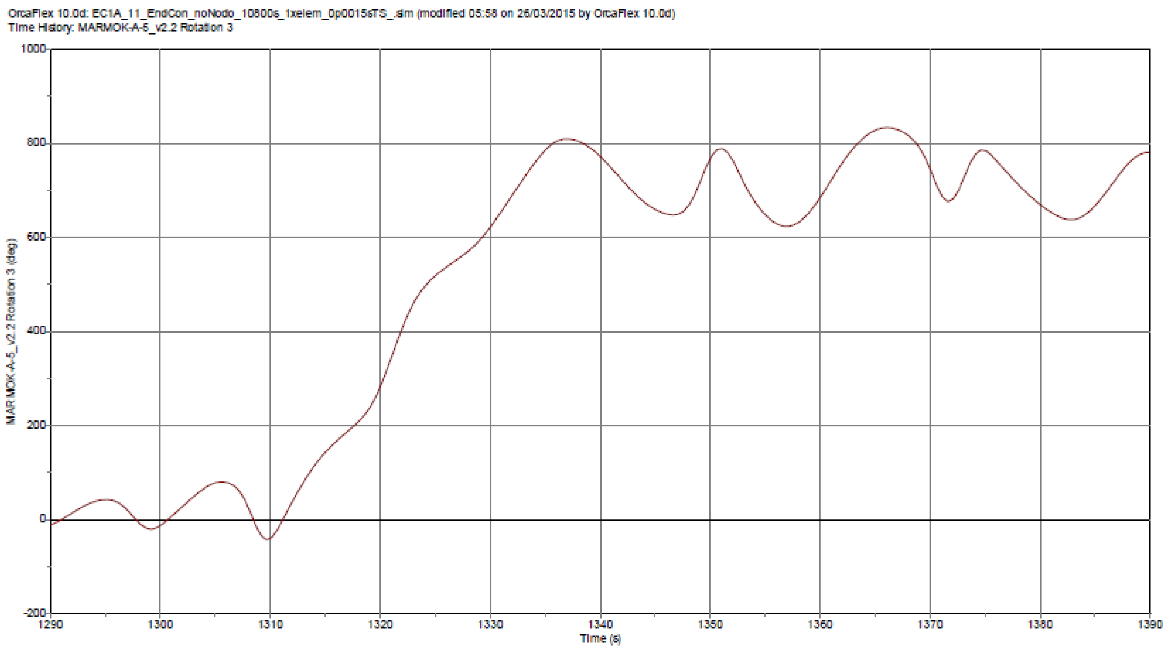


FIGURE. 3-33 YAW (ROTATION 3) ROTATED TO CIRCA 720 DEG AT 1335S

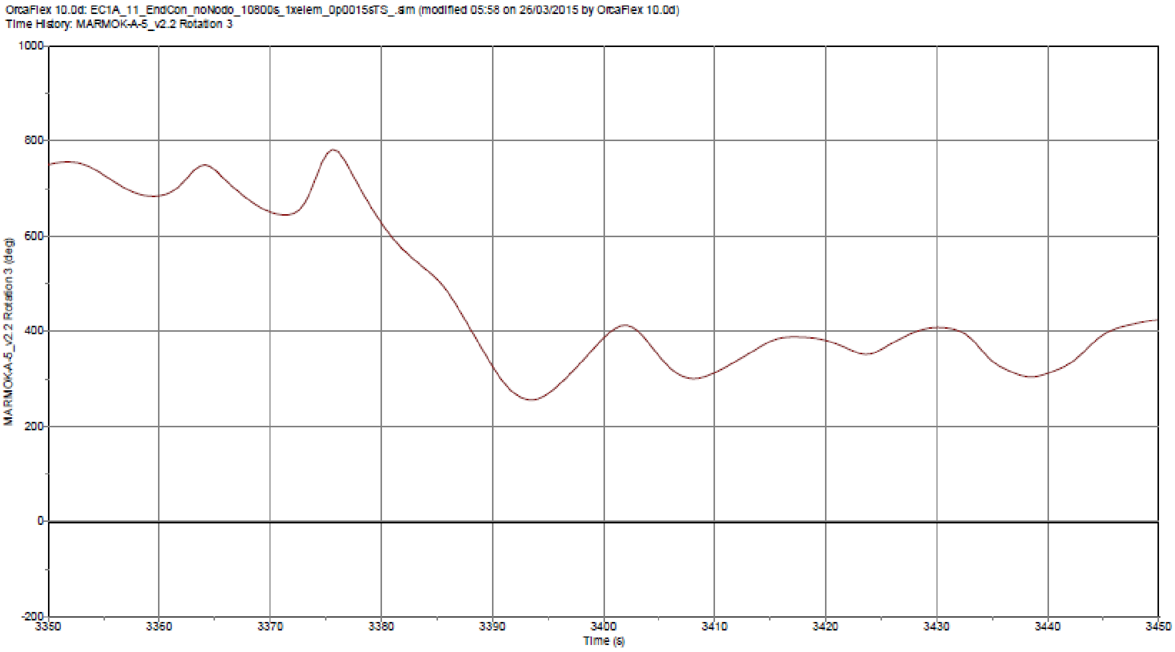


FIGURE. 3-34 YAW (ROTATION 3) ROTATED TO CIRCA 360 DEG AT 3394S

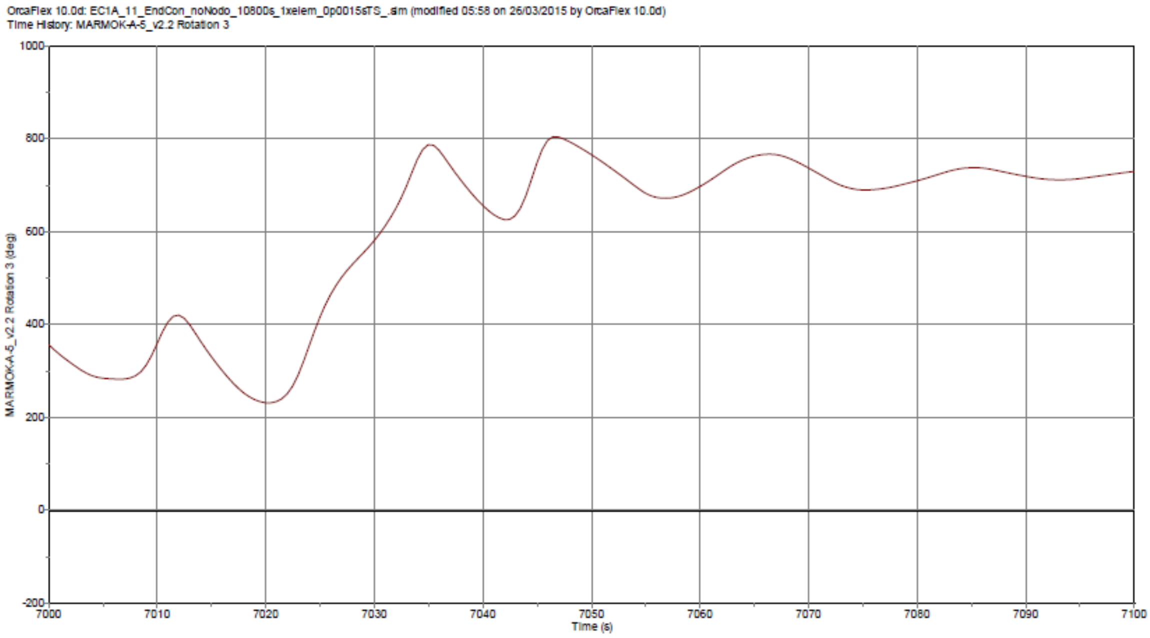


FIGURE. 3-35 YAW (ROTATION 3) ROTATED TO CIRCA 720 DEG AT 7035S

The associated line tensions of the Conex 1 are presented in Figure. 3-36 to Figure. 3-38.

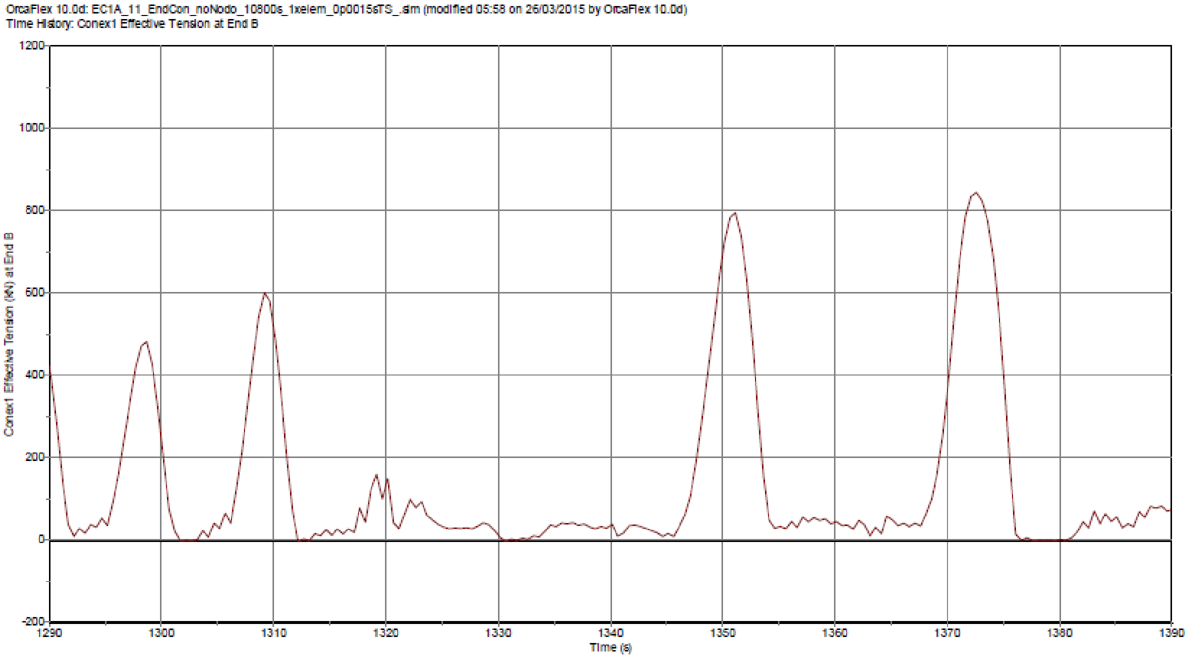


FIGURE. 3-36 CONEX 1 (END B) PEAK TENSION OBSERVED FROM 1290S TO 1390S

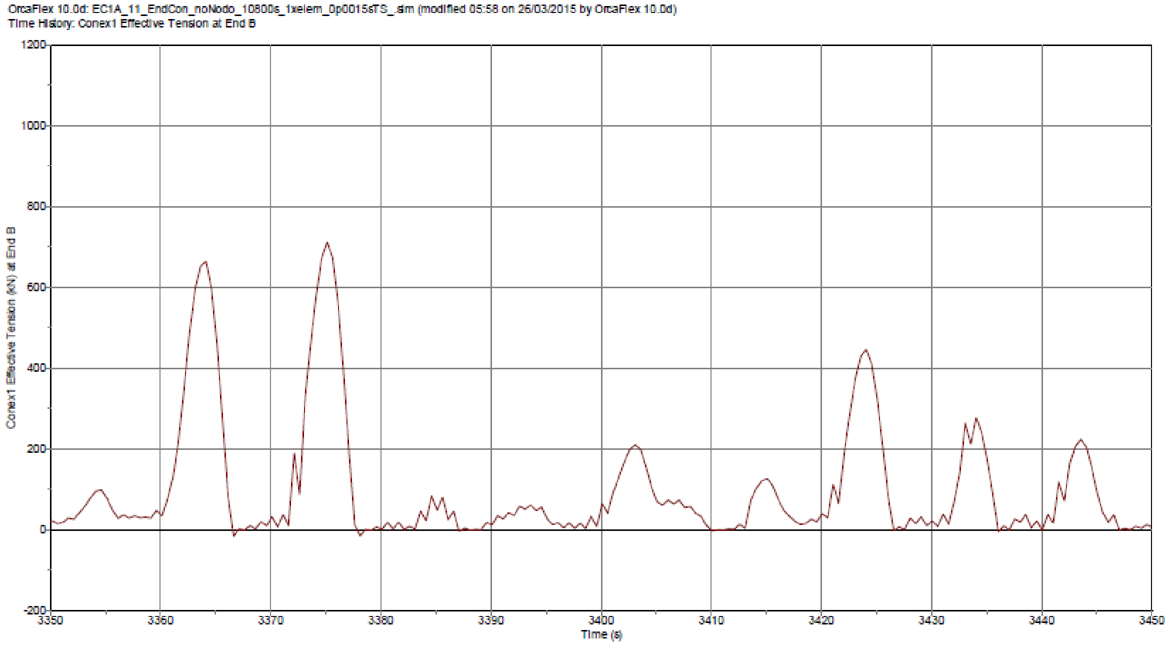


FIGURE. 3-37 CONEX 1 (END B) PEAK TENSION OBSERVED FROM 3350S TO 3450S

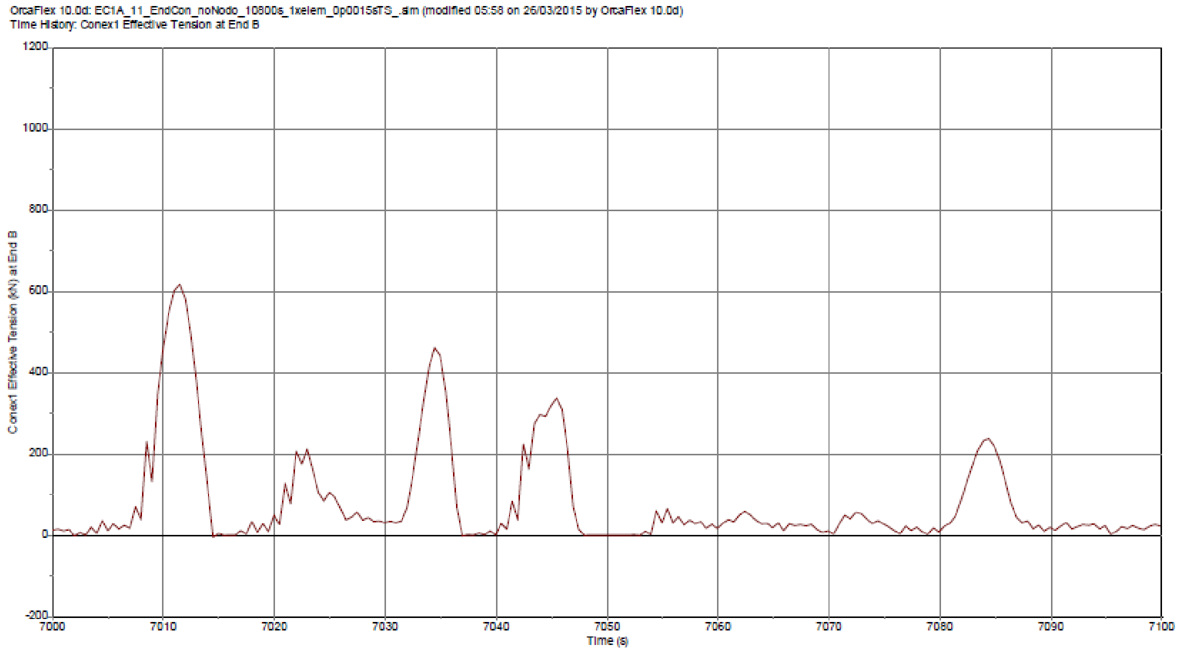


FIGURE. 3-38 CONEX 1 (END B) PEAK TENSION OBSERVED FROM 7000S TO 7100S

Figure. 3-39 and Figure. 3-40 show the Conex lines passing through the hull un-impeded in model.

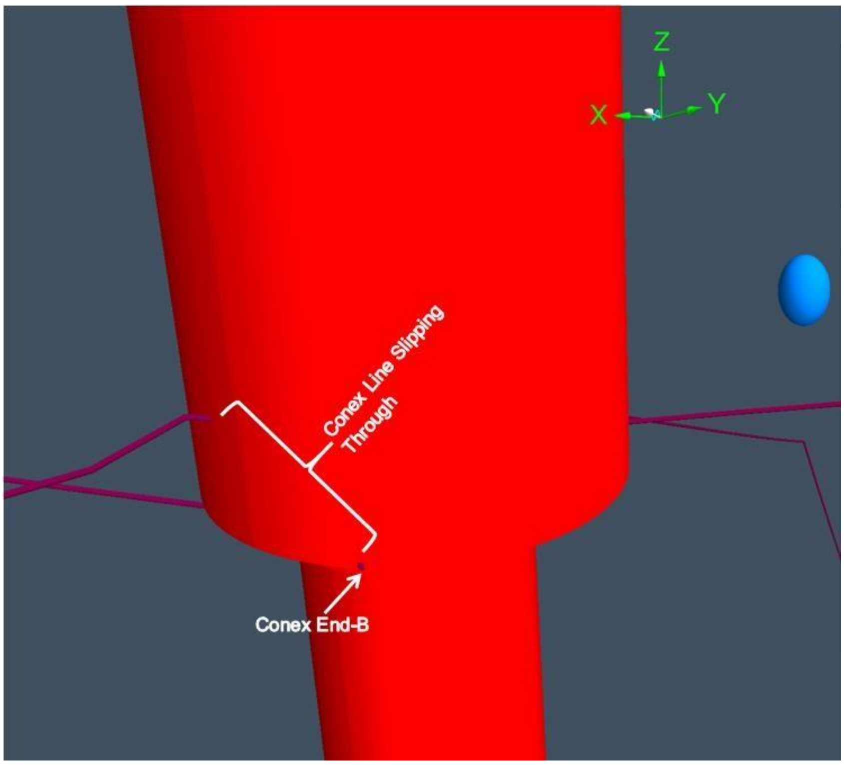


FIGURE. 3-39 CONEX LINE SLIPPING THROUGH – RENDERED VIEW

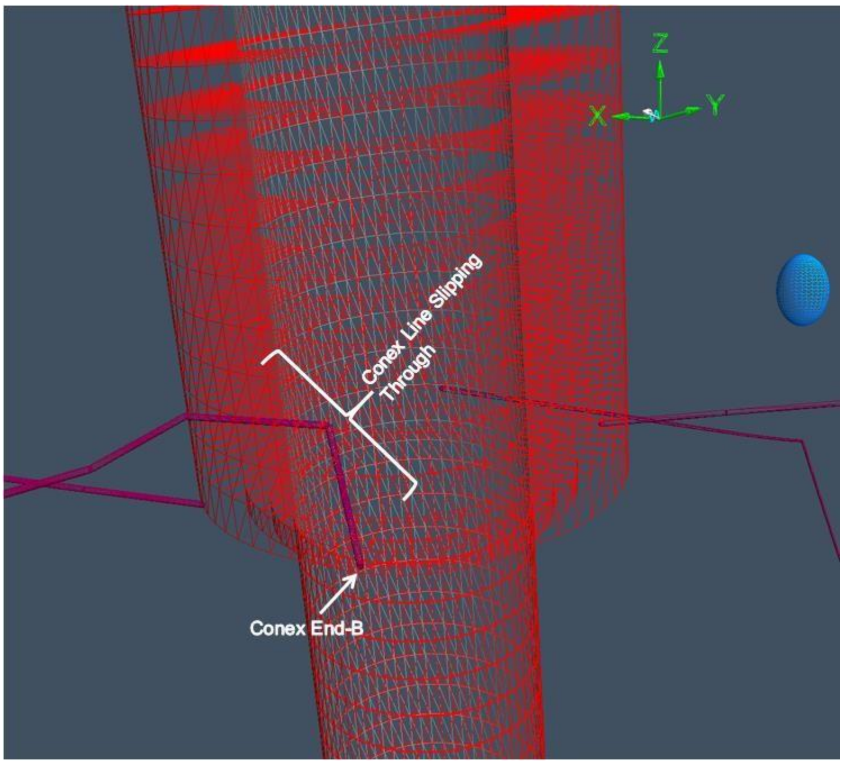


FIGURE. 3-40 CONEX LINE SLIPPING THROUGH – MESH VIEW

3.3.2 EFFECT OF LINEAR YAW DAMPING

Orcaflex offers the user the option to model yaw damping of the floater by means of specifying the 'Unit Damping Moment (UDM)' per cylinder. In the original model this was set to zero. The Yaw (Rotation 3) of the original model is presented in Figure. 3-41.

The effect of implementing the linear yaw damping on the WEC model have been investigated for the UDM values of 0.01, 0.1, 1.0, 10 and 100 kNm/(rad/s). To expedite the analyses a reduced number of elements per mooring line have been used (Half x Element), and a larger time step employed (0.048sec).

The time trace plots for the Yaw (Rotation 3) of the model with UDM are presented in Figure. 3-42 to Figure. 3-46. These show that the large yaw rotations occur for UDMs of 0.01 and 0.1 kNm/(rad/s). At a value of 1.0 kNm/(rad/s) UDM large yaw rotations do not occur. For larger values of UDM (10, 100 kNm/(rad/s)) the yaw rotation appears to be overdamped.

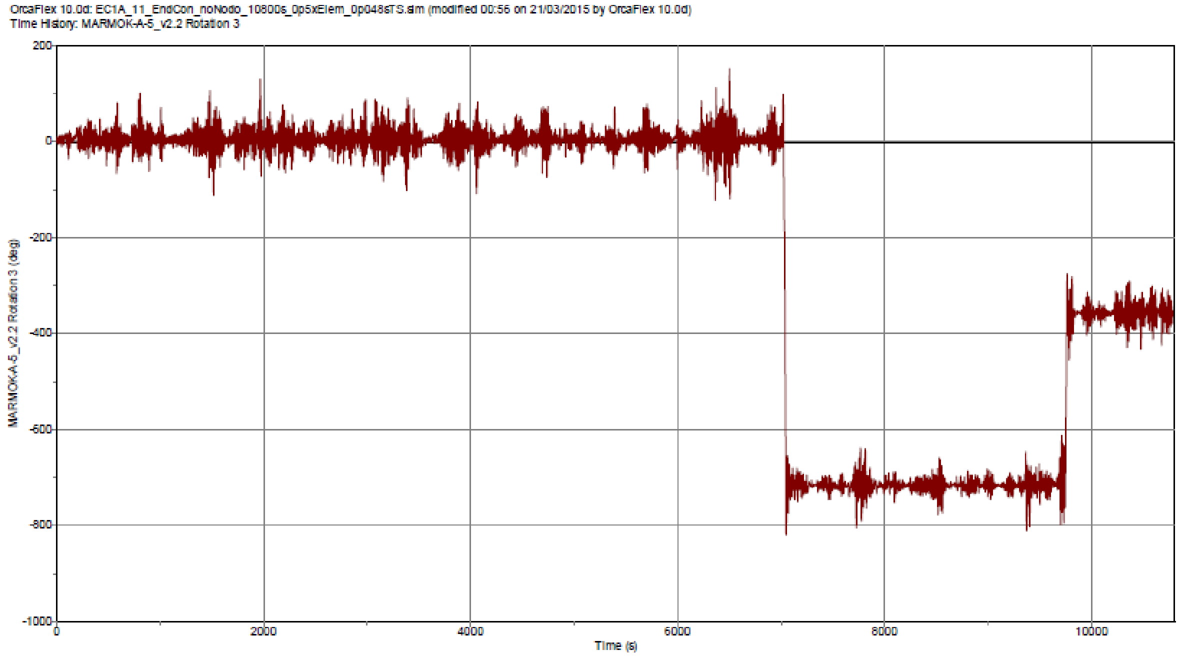


FIGURE. 3-41 ROTATION 3 – UDM = 0 KN-M/(RAD/S), ORIGINAL MODEL

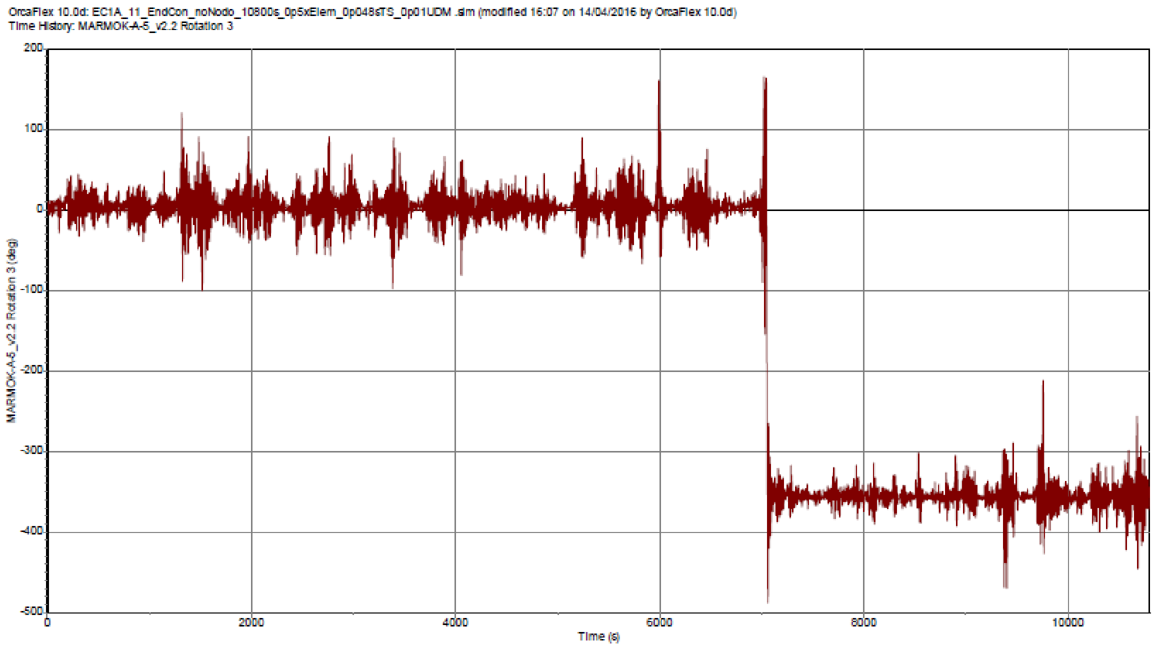


FIGURE. 3-42 ROTATION 3 – UDM = 0.01 KN-M/(RAD/S)

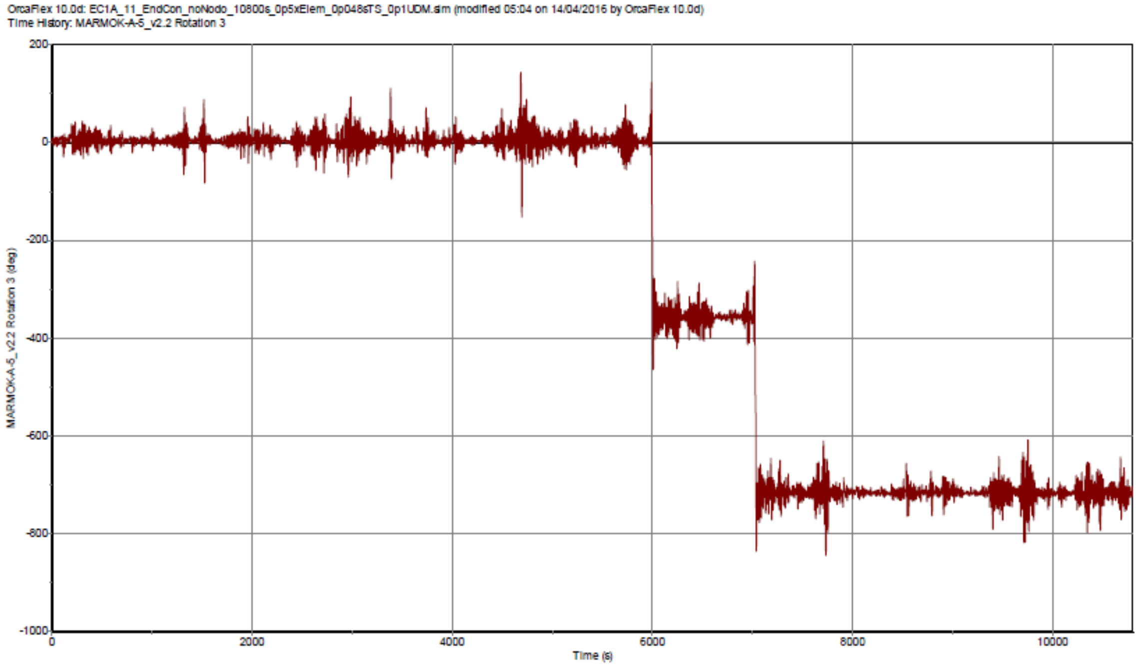


FIGURE. 3-43 ROTATION 3 – UDM = 0.1 KN-M/(RAD/S)

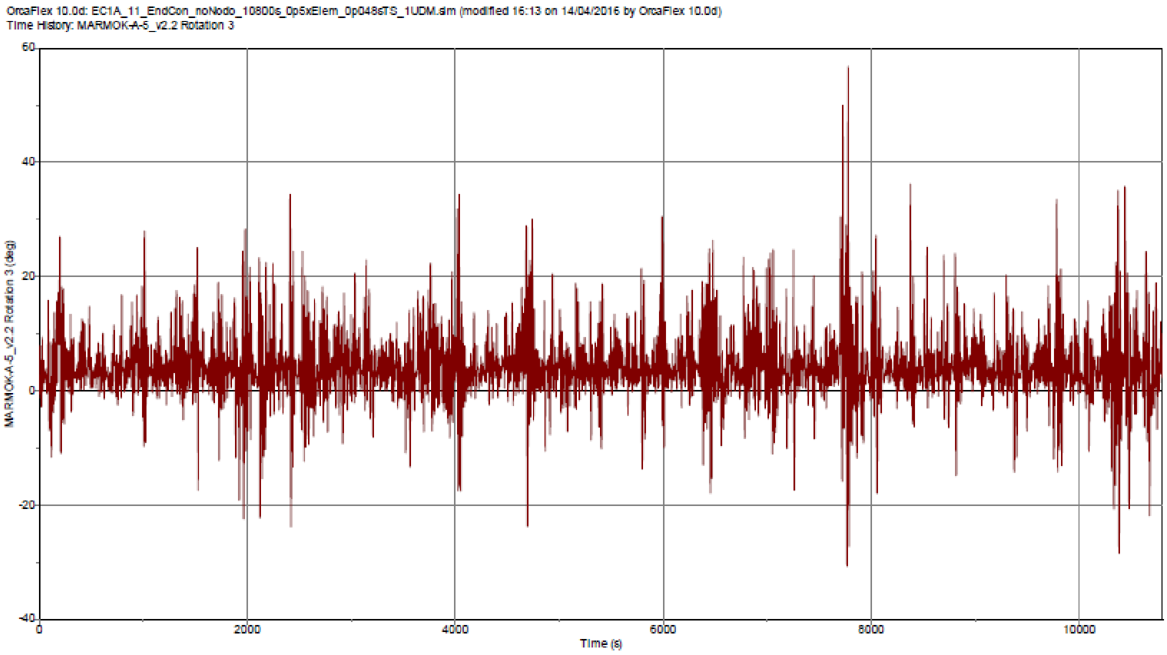


FIGURE. 3-44 ROTATION 3 – UDM = 1.0 KN-M/(RAD/S)

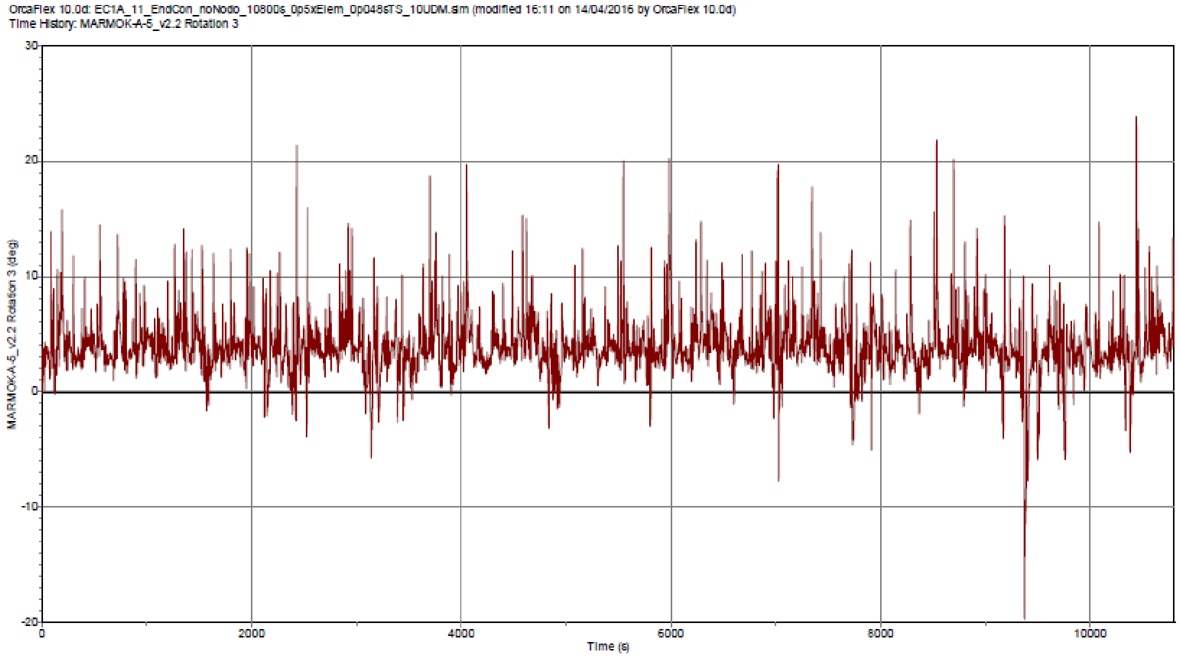


FIGURE. 3-45 ROTATION 3 – UDM = 10.0 KN-M/(RAD/S)

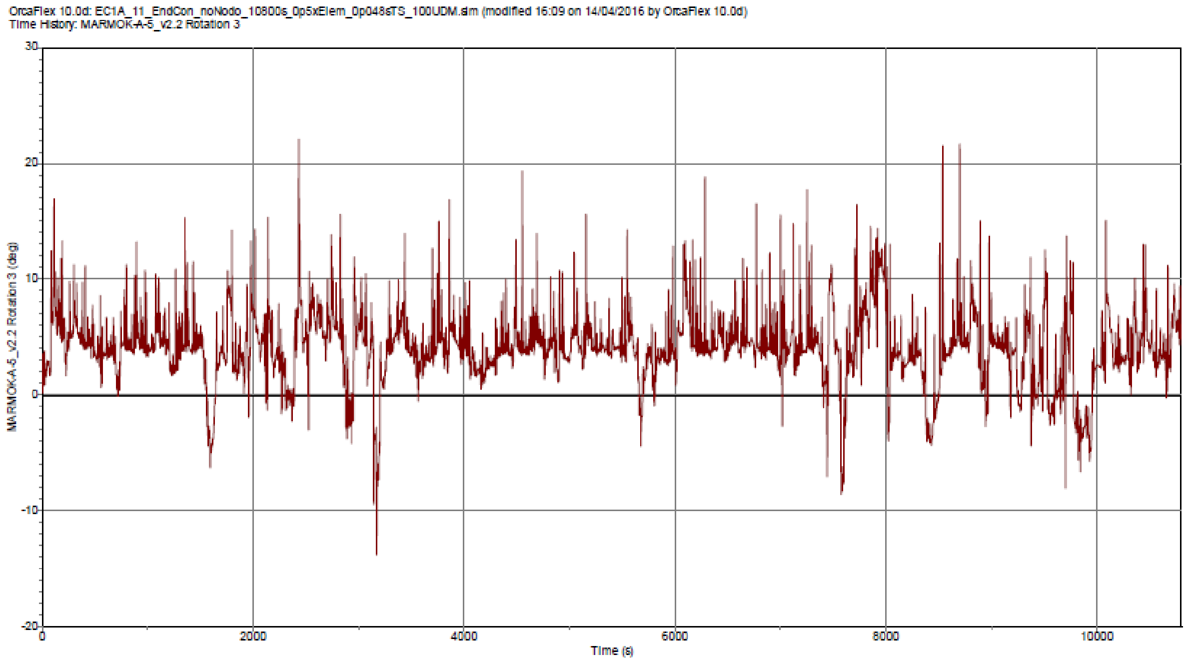


FIGURE. 3-46 ROTATION 3 – UDM = 100.0 KN-M/(RAD/S)

The statistics of the Yaw rotation are presented in Table. 3-14 for the various levels of UDM. It is seen that a significant change occurs in the Yaw rotation when the UDM per cylinder reaches 1 kNm/(rad/sec).

TABLE. 3-14 WEC ROTATION 3 SUMMARY – EFFECT OF UDM

UDM (kNm/(rad/s))	0 (Default)	0.01	0.1	1	10	100
Minimum	-819.6	-487.7	-844.4	-30.7	-19.7	-13.9
Maximum	152.6	165.2	143.7	56.8	23.9	22.1
Mean	-211.9	-120.8	-281.6	4.4	4.0	4.1
Std Dev	311.6	173.0	335.4	6.7	2.7	3.2

3.3.3 EFFECT OF EXTENDING FAIRLEAD POSITION

A test has been performed on the extending the fairlead node locations (Conex End-B). In this test, the fairlead nodes have been extended outboard by 2m from the original position. Overview of this modification is shown in Figure. 3-47 (original position) and Figure. 3-48 (extended position).

The time trace plots for the Yaw (Rotation 3) of the model with original fairlead position and model with extended fairlead position are presented in Figure. 3-49 and Figure. 3-50 respectively.

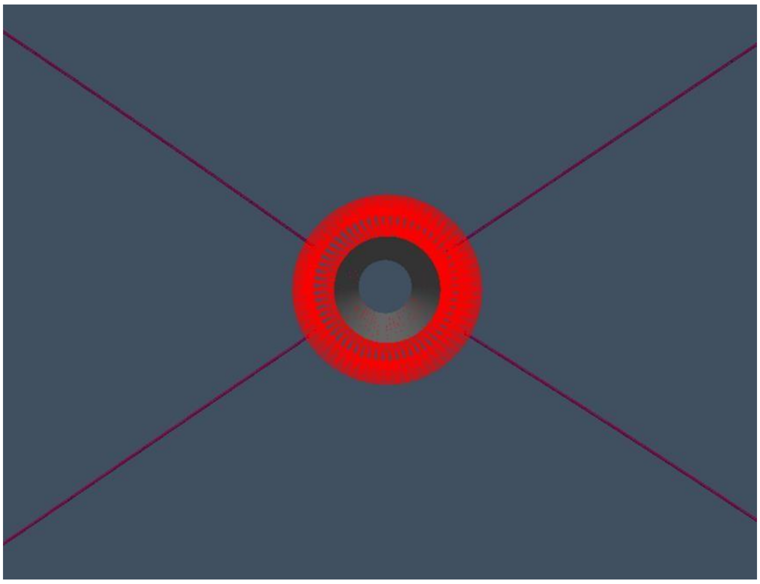


FIGURE. 3-47 ORIGINAL FAIRLEAD POSITION

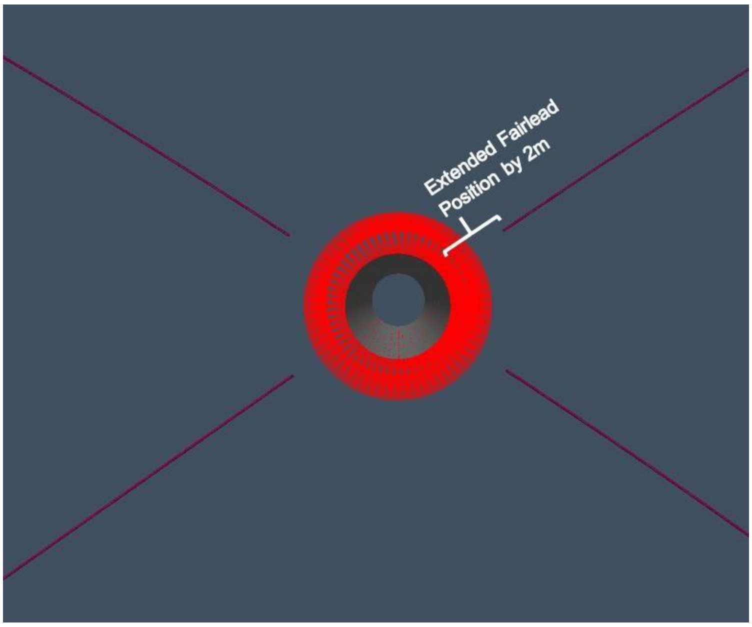


FIGURE. 3-48 FAIRLEAD POSITION EXTENDED 2M OUTWARD

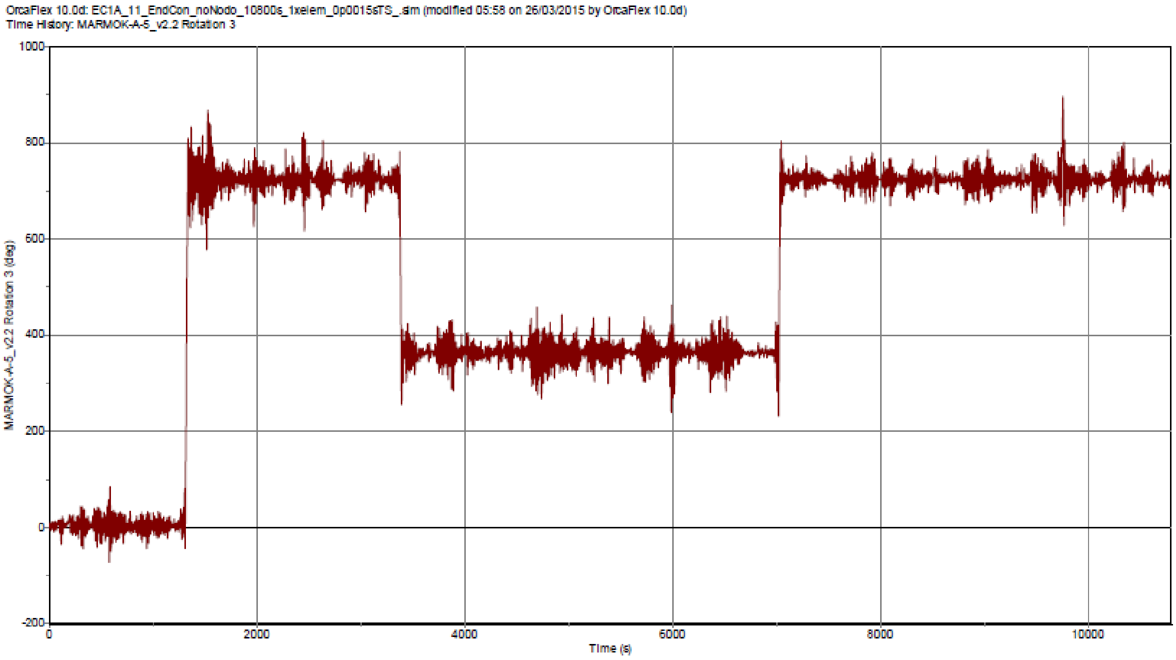


FIGURE. 3-49 ROTATION 3 – ORIGINAL FAIRLEAD POSITION

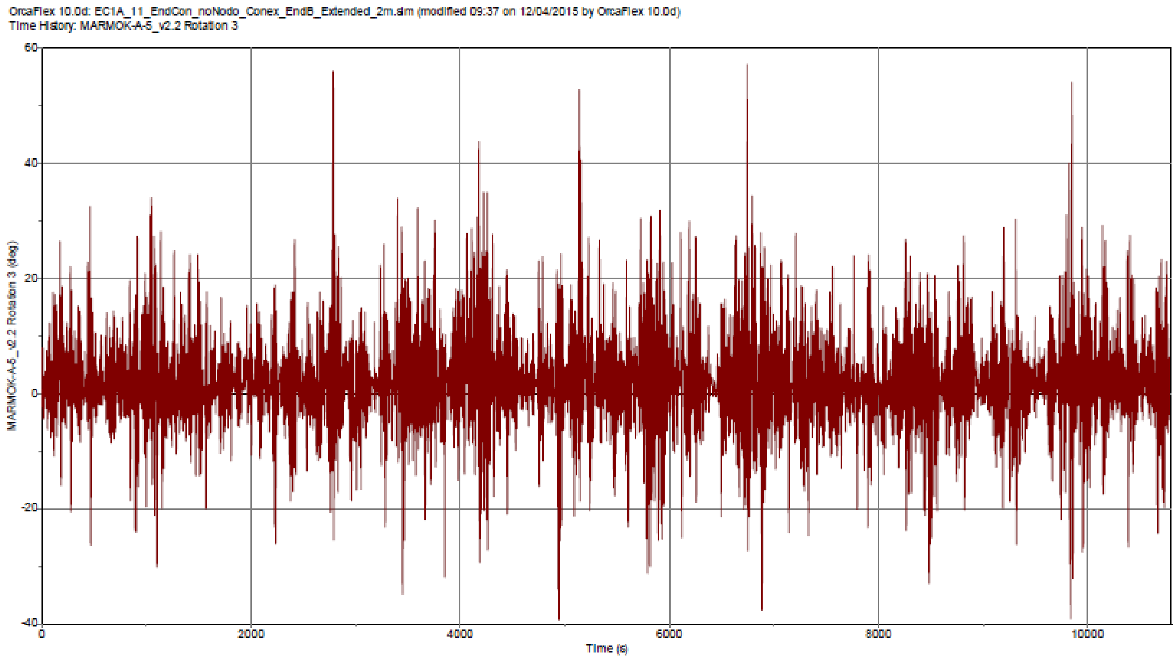


FIGURE. 3-50 ROTATION 3 – FAIRLEAD POSITION EXTENDED 2M OUTWARD

TABLE. 3-15 YAW (ROTATION 3) STATISTICS - WITH & WITHOUT FAIRLEAD EXTENSION

	Yaw Rotation (deg)	
Fairlead position	Original	Extended 2m
Minimum	-73.0	-39.3
Maximum	897.1	57.2
Mean	514.0	2.1
Std Dev	252.7	9.5

From the time trace plot presented in Figure. 3-50 and

Table. 3-15, it is observed that by extending the Conex End-B outward, the Yaw rotations are significantly reduced.

3.3.4 EFFECT OF CONTACT SURFACE

Mooring lines were observed to pass through the hull of the MARMOK, see Figure. 3-39 and Figure. 3-40. This obviously is not possible in reality. Hence Elastic Solid Shapes were introduced in the model that present physical barrier to the mooring lines passing through the hull Figure. 3-51 presents a picture of the Elastic Solid Shapes employed in the model.

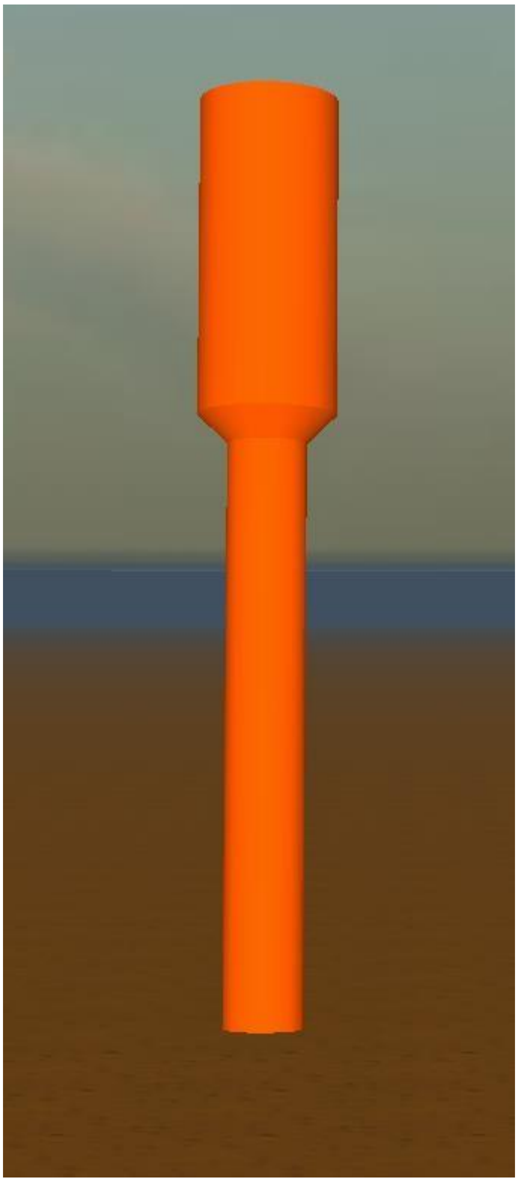


FIGURE. 3-51 ELASTIC SOLID SHAPE

To expedite the analysis a larger time step of 0.006s was employed, with the original number of elements (1 x Elem). Figure. 3-52 presents the Yaw rotation without any Elastic Solid Shapes, which shows large rotations. Figure. 3-53 presents the Yaw rotation with Elastic Solid Shapes, which shows that the Yaw rotations have reduced.

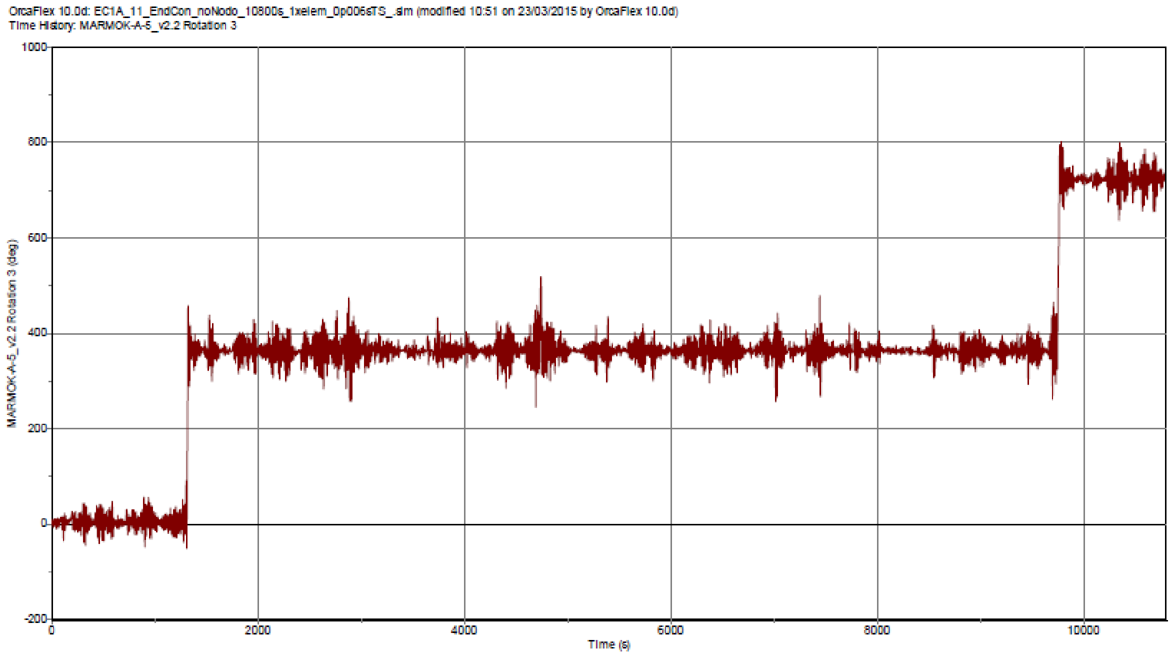


FIGURE. 3-52 YAW (ROTATION 3) – WEC WITHOUT ELASTIC SOLID SURFACE

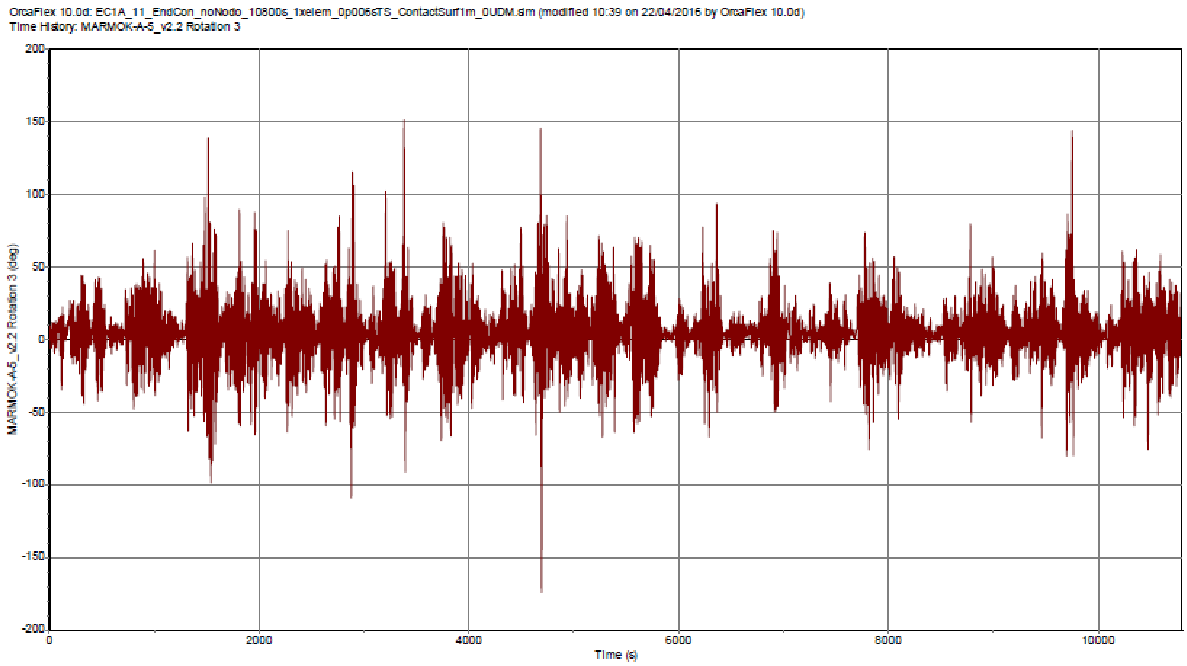


FIGURE. 3-53 YAW (ROTATION 3) – WEC WITH ELASTIC SOLID SURFACE

Application of the Elastic Solid Shape dramatically changes the amount of yaw, as seen in Figure. 3-53 and Table. 3-16. The range is more evenly balanced between –ve and +ve yaw rotations, and the range is -170 deg to +150 deg.

TABLE. 3-16 YAW (ROTATION 3) STATISTICS - WITH & WITHOUT ELASTIC SOLID SHAPE

	Yaw Rotation (deg)	
Elastic Solid Shape:	**None**	**Present**
Minimum	-50.2	-174.5
Maximum	801.9	151.0
Mean	355.4	4.6
Std Dev	169.1	24.8

3.3.5 RECOMMENDATIONS FOR FUTURE WORK

The 3-hour time domain simulations of the basis moored MARMOK model have indicated that very large rotations (greater than 360deg) are predicted. For various reasons it is queried whether this is realistic. Hence various investigations have been undertaken on specific aspects of the model:

- Linear yaw damping
- Extension of the fairlead connection outboard
- Elastic solid shapes

The linear yaw damping has a significant effect on the yaw rotations; a value of 1.0 kNm/(rad/sec) reduces the rotation substantially. However, it is not yet clear what an appropriate amount of yaw damping should be, and it is recommended that a realistic value is identified.

Fairlead Extension - artificially extending the fairlead outboard by 2m also significantly reduces the yaw rotation. However, as the extension is artificial, it is recommended that the fairlead is only extended outboard to represent the actual fairlead position.

Elastic Solid Shapes – in order to avoid the mooring lines appearing to cut through the MARMOK, elastic solid shapes have been introduced to model the mooring lines wrap around the outside of the MARMOK. This also significantly reduces the amount yaw rotation. It is recommended that this is incorporated into future models.

4. ENVIRONMENTAL PARAMETERS

The dates and times of the environments that have been used in the validation process for P1 are:

- Low environment — 6th May 2017, 10:00 hrs
- Storm sequence — 28th June 2017, 12:00 – 24:00 hrs
- Medium environment — 28th June 2017, 12:00 hrs
- Extreme environment — 28th June 2017, 20:00 hrs

The results presented here for P1 are an update of the results presented in WP2_GM_108, where detailed current profile from an ADCP has been included in the Orcaflex model.

Moreover, the MARMOK added mass and drag has been updated; and a 6% permanent elongation of the polyester lines has been assumed.

Environments with parameters similar to the P1 deployment are considered for P2 to facilitate a comparison of mooring response characteristics between the two deployment phases. The dates and times for P2 environments are as follows:

- Low environment — 30th December 2018, 13:00 hrs
- Medium environment — 23rd December 2018, 14:00 hrs
- Extreme environment — 14th December 2018, 11:00 hrs

It is assumed that the time stamp associated with each parameter recording are accurately synchronized.

4.1 LOW ENVIRONMENT

The low environment for P1 occurred on the 6th May 2017, herein referred to as ENV000P1. Principal wind, wave, current and tidal level parameters, and current profile are plotted in Figure. 4-1 to Figure. 4-10. The environment at 10:00 hr has been selected on the basis that the current regime is small (circa 0.025m/s) and the Hs is small (<0.5m).

The low environment for P2 has been selected based on similarity to the low environment in P1. The low environment for P2 occurred on the 30th December 2018, herein referred to as ENV000P2.In summary the environmental parameters are presented in Table. 4-1.

TABLE. 4-1 LOW ENVIRONMENT PARAMETERS FOR P1 AND P2

	Date, Time	Wind	Wave	Current	Tide
ENV000P1	06/05/2017, 10:00:00	4.54m/s mean hourly 320deg Dir	0.56m Hs 11s Tp 303deg Dir	0.0264m/s 75deg Direction toward (255deg direction from)	+0.7m
ENV000P2	30/12/2018 13:00:00	3.906m/s mean hourly 73.125deg dir	0.58 m Hs 11.16 s Tp 324.84deg Dir	0.21 m/s 265.78	

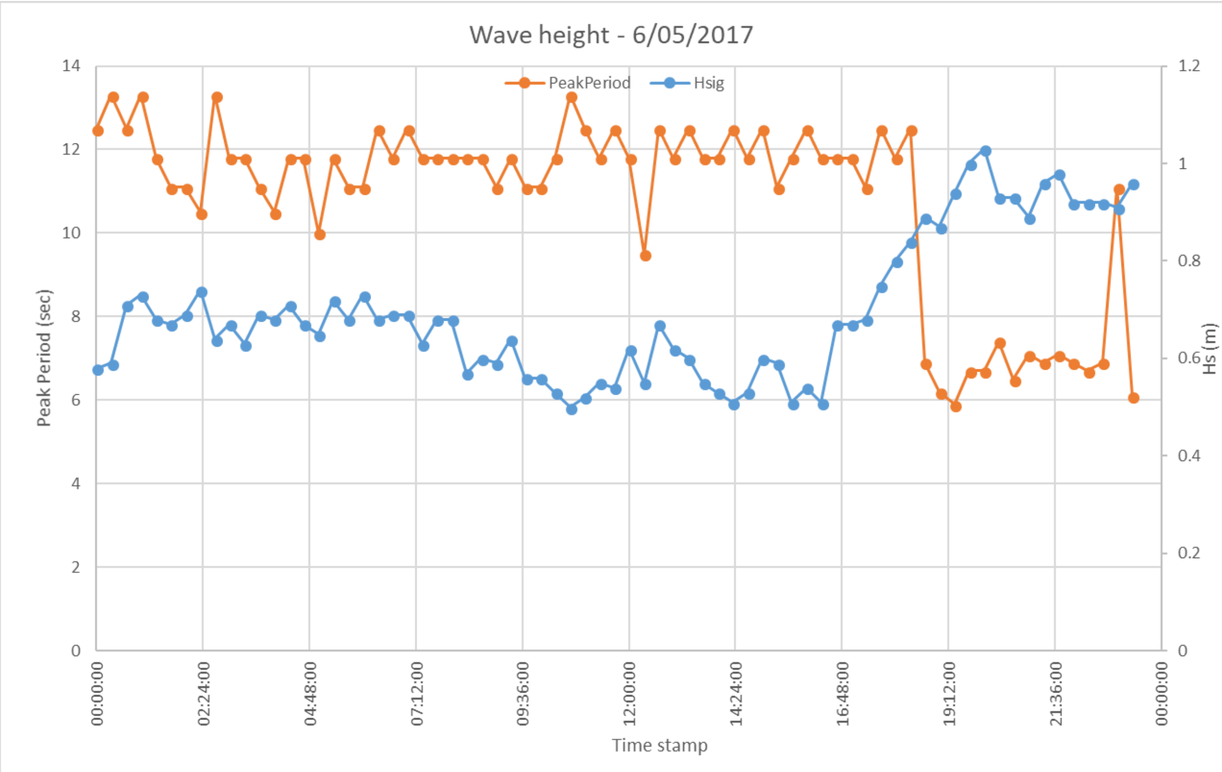


FIGURE. 4-1 ENV000P1: WAVE HEIGHT ON 06/05/2017

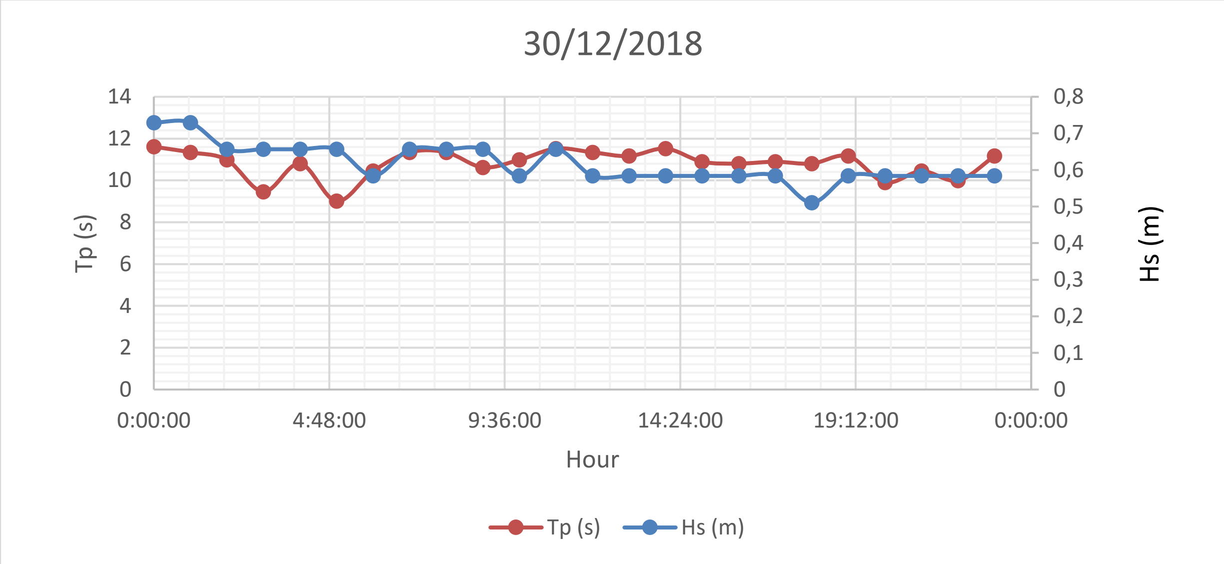


FIGURE. 4-2 ENV000P2: WAVE HEIGHT ON 30/12/2018

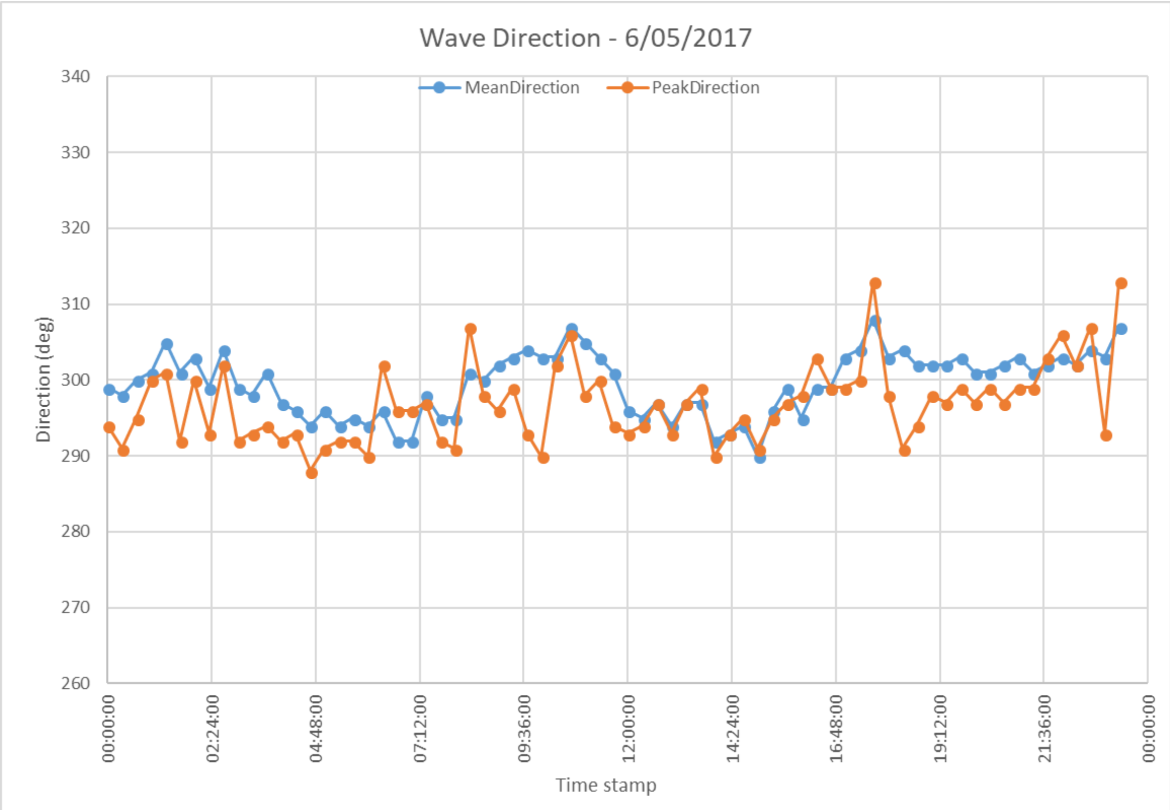


FIGURE. 4-3 ENV000P1: WAVE DIRECTION ON 06/05/2017

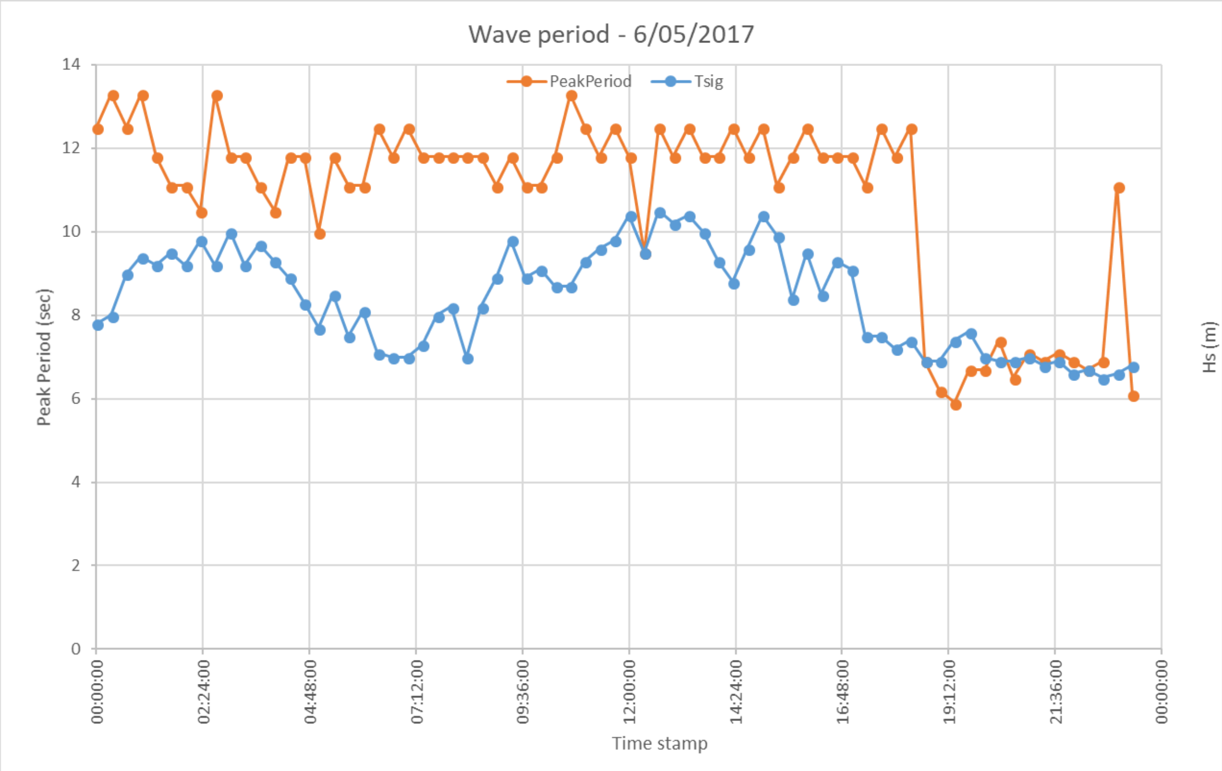


FIGURE. 4-4 ENV000P1: WAVE PERIOD ON 06/05/2017

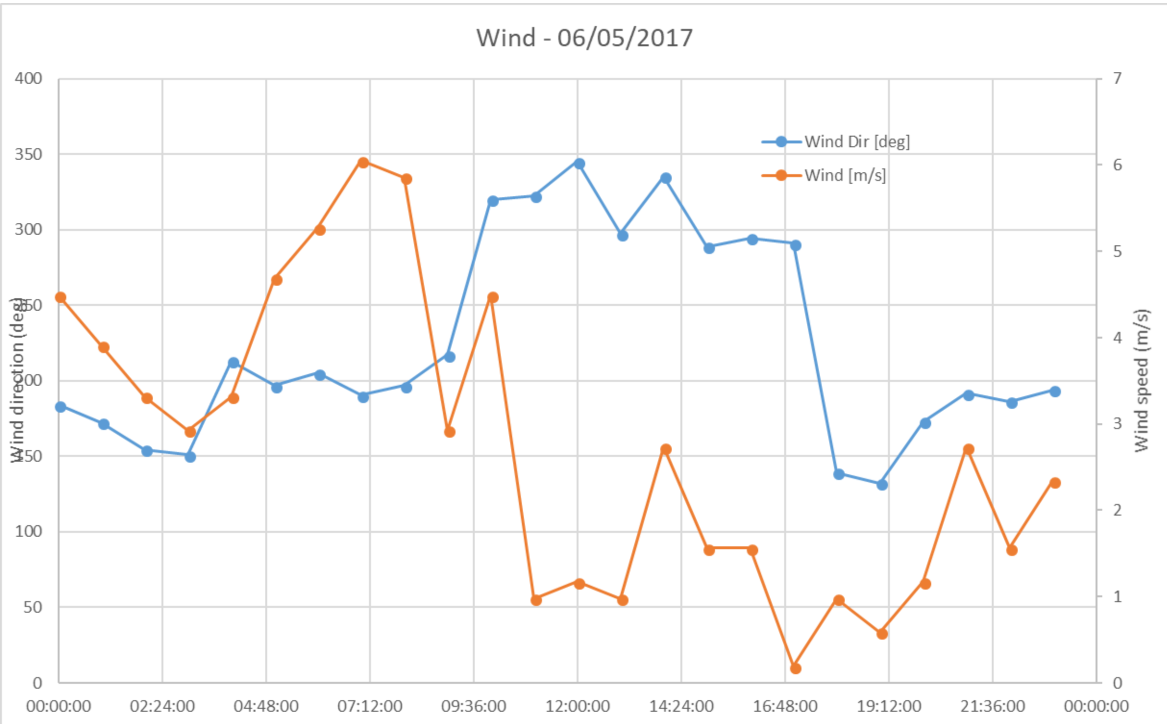


FIGURE. 4-5 ENV000P1: WIND SPEED AND DIRECTION ON 06/05/2017

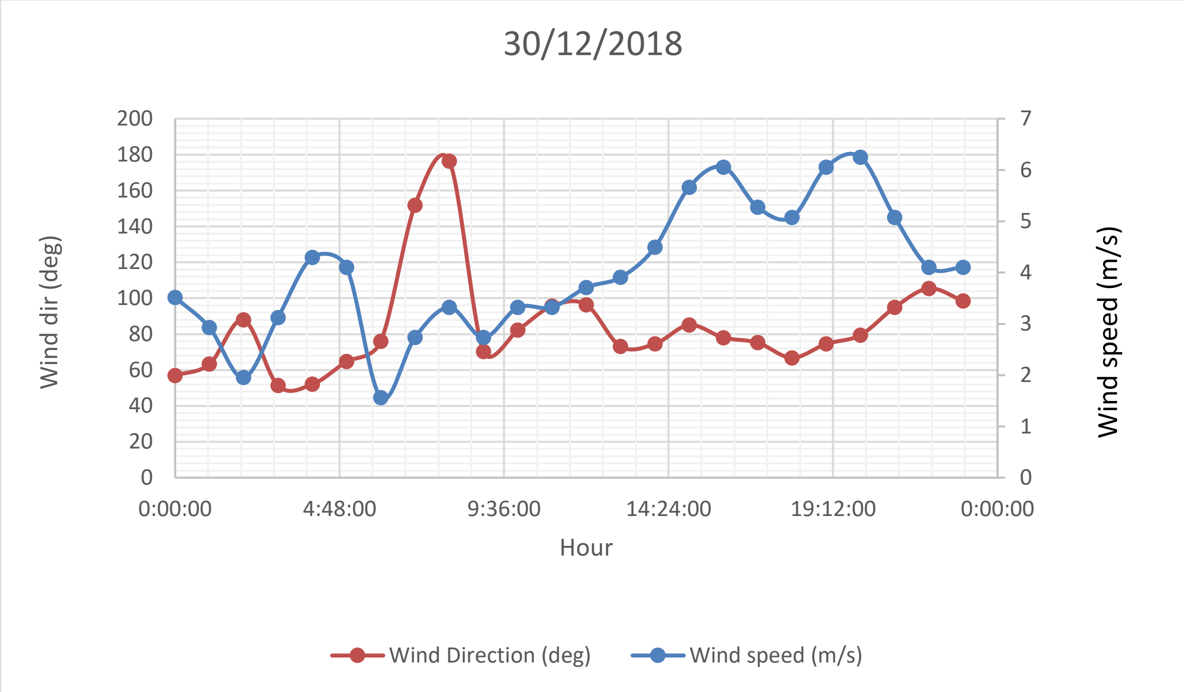


FIGURE. 4-6 ENV000P2: WIND SPEED AND DIRECTION ON 30/12/2018

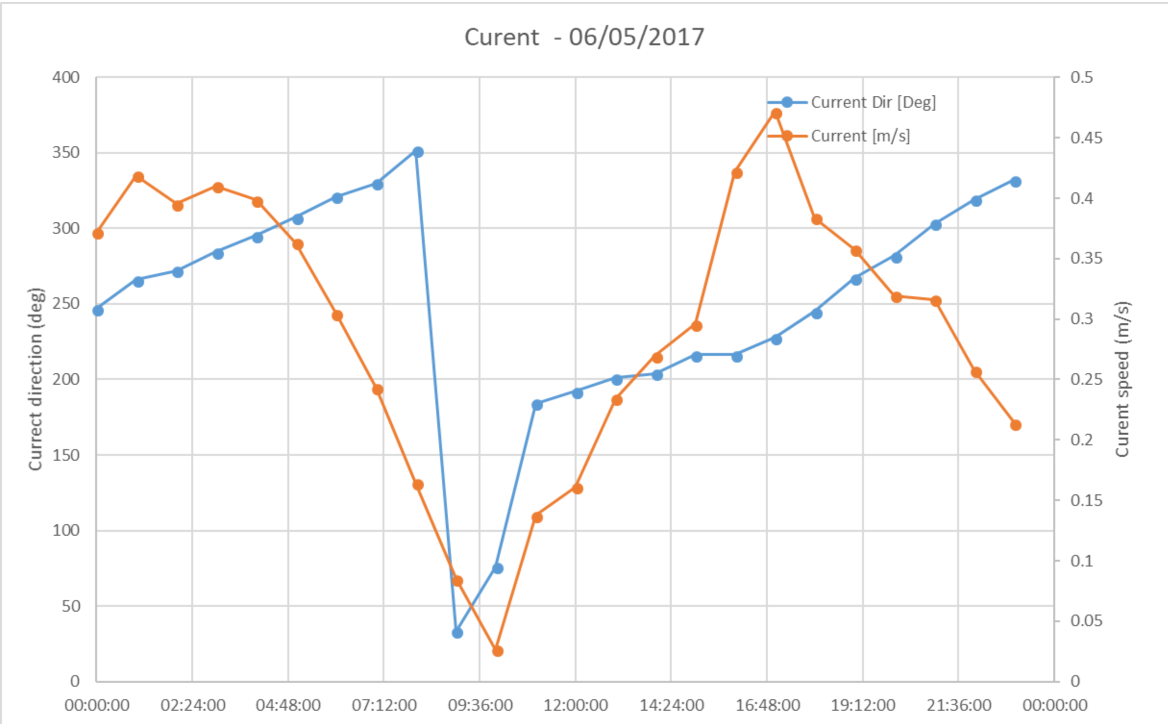


FIGURE. 4-7 ENV000P1: CURRENT SPEED AND DIRECTION ON 06/05/2017

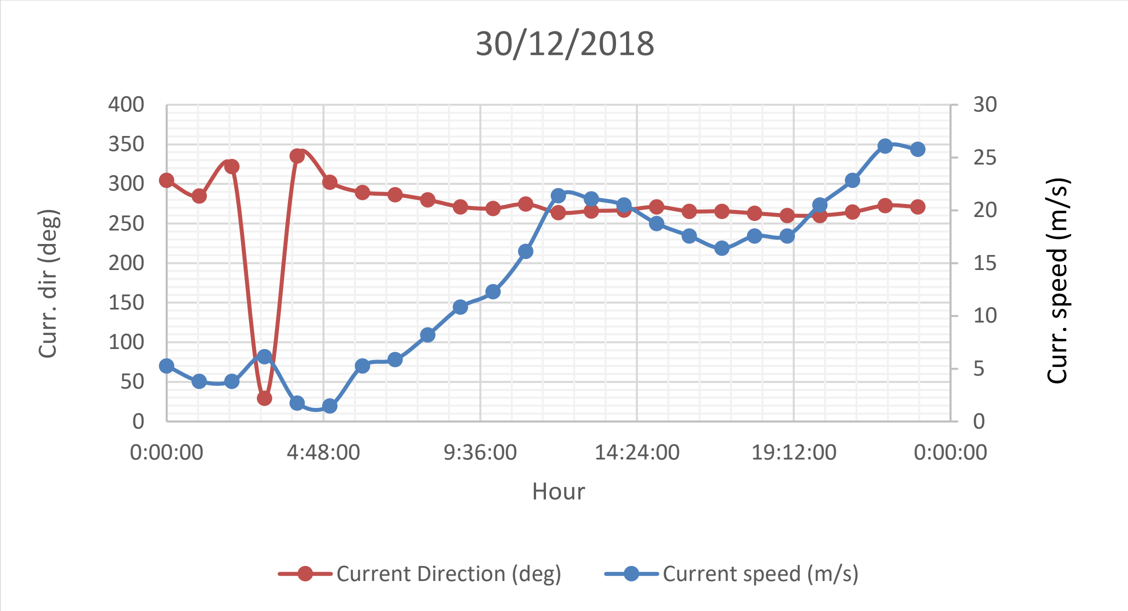


FIGURE. 4-8 ENV000P2: CURRENT SPEED AND DIRECTION ON 30/12/2018

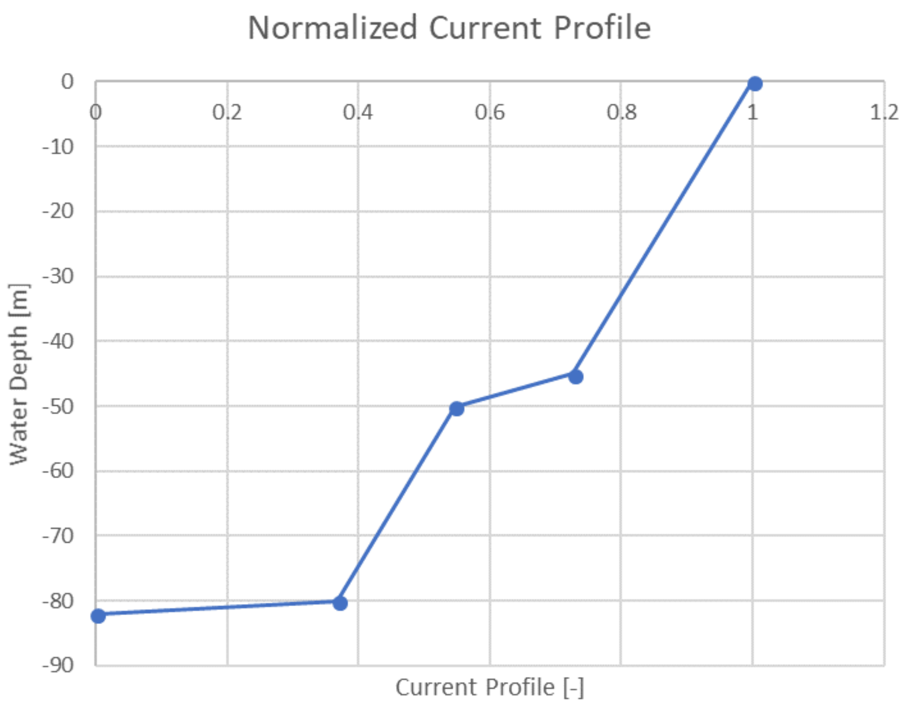


FIGURE. 4-9 CURRENT PROFILE USED FOR ALL ENV000

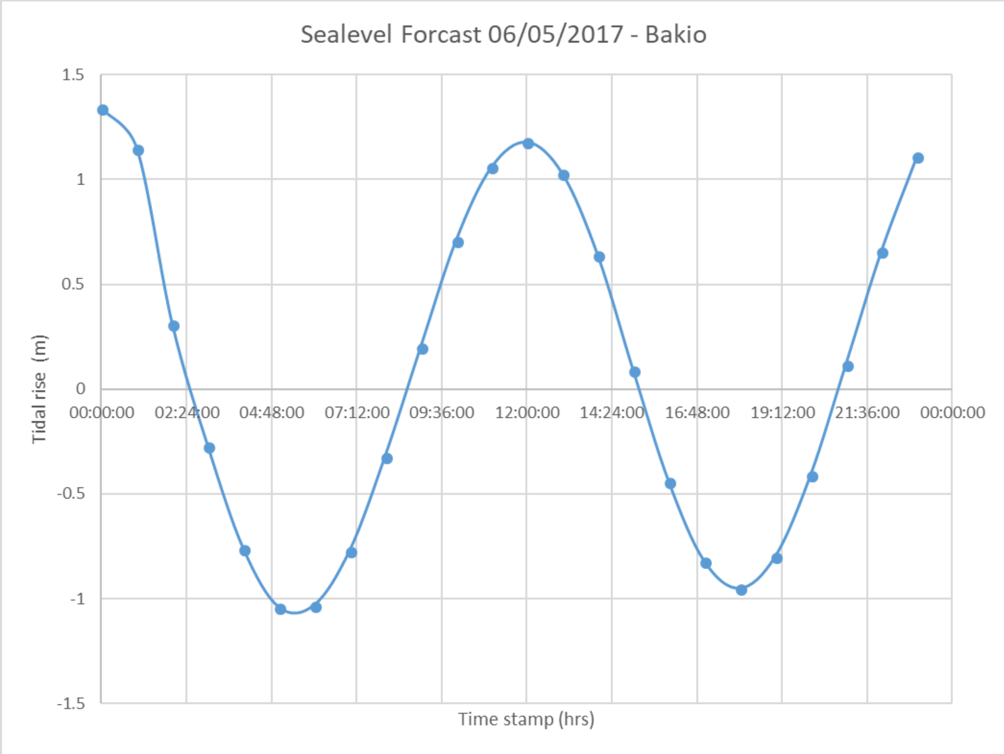


FIGURE. 4-10 ENV000P1: TIDAL LEVEL AT BAKIO, NEAR MARMOK ON 06/05/2017

4.2 STORM ENVIRONMENT

The storm environment occurred on the 28/06/17 for P1. The developing storm environment has been analysed for 4 x 20 minute portions of time (ENV101P1 through to ENV104P1).

The wave-rider buoy local to MARMOK was the Triaxys buoy, a summary of its wave parameters are presented in Table. 4-2 for Phase 1 deployment.

TABLE. 4-2 TRIAXYS WAVE BUOY FOR P1

			Axys wave buoy (summary values)				
Code	Date	Ti me	Hs [m]	Tp [s]	Wav Dir [deg]	UTM X [m]	UTM Y [m]
ENV101P1	28/06/2017	12:00:00	1.06	8.3	300	510508.038	4813154.765
ENV102P1	28/06/2017	16:00:00	3.44	9.1	301	510529.553	4813154.799
ENV103P1	28/06/2017	20:00:00	5.58	11.8	297	510530.890	4813178.900
ENV104P1	29/06/2017	00:00:00	3.87	11.8	296	510543.005	4813190.025

Two environments were chosen for P2 to provide a comparison for medium and extreme environmental conditions. The medium environment for P2, ENV101P2, was chosen to be comparable with ENV101P1 and the extreme environment, ENV103P2, was chosen to be comparable to ENV103P1.

TABLE. 4-3 FUGRO WAVE BUOY FOR P2

Code	Date	Time	Hs [m]	Tp [s]	Wav Dir [deg]	UTM X [m]	UTM Y [m]
ENV101P2	23/12/2018	14:00:00	1.17	9.1	308	-	-
ENV103P2	14/12/2018	11:00:00	4.6	16.02	312.19	-	-

The Triaxys buoy also offered spectral ordinate data of the measured seastate for P1, see Figure. 4-11, in addition to the summary values of Hs and Tp. A summary of the difference between summary values and Spectral measured values of significant wave height from the Triaxys wave buoy are presented in Table. 4-4.

TABLE. 4-4 HS DIFFERENCE – SUMMARY AND SPECTRAL ORDINATE VALUES

	Hs Axys [m]	Hs from m0 [m]	Difference [m]
ENV101P1	**1.060**	1.144	0.084
ENV102P1	**3.440**	3.519	0.079
ENV103P1	**5.580**	5.866	0.286
ENV104P1	**3.870**	4.031	0.161

The Tp values used for the analysis have been estimated from the spectral moments of the Triaxys spectral ordinates as per equation: $Tp = \frac{\int S(\omega)^4 d\omega}{\int \omega S(\omega)^4 d\omega}$

The difference in Tp values are presented in Table. 4-5 below:

TABLE. 4-5 ENVIRONMENT PEAK PERIODS

	Tp Axys [s]	Tp estimate [s]	Difference [s]
ENV101P1	**8.333**	7.749	-0.584
ENV102P1	**9.091**	8.481	-0.610
ENV103P1	**11.765**	10.899	-0.866
ENV104P1	**11.765**	11.644	-0.121

Because of the differences in reported Hs and Tp, an idealized spectra has not been considered for this study.

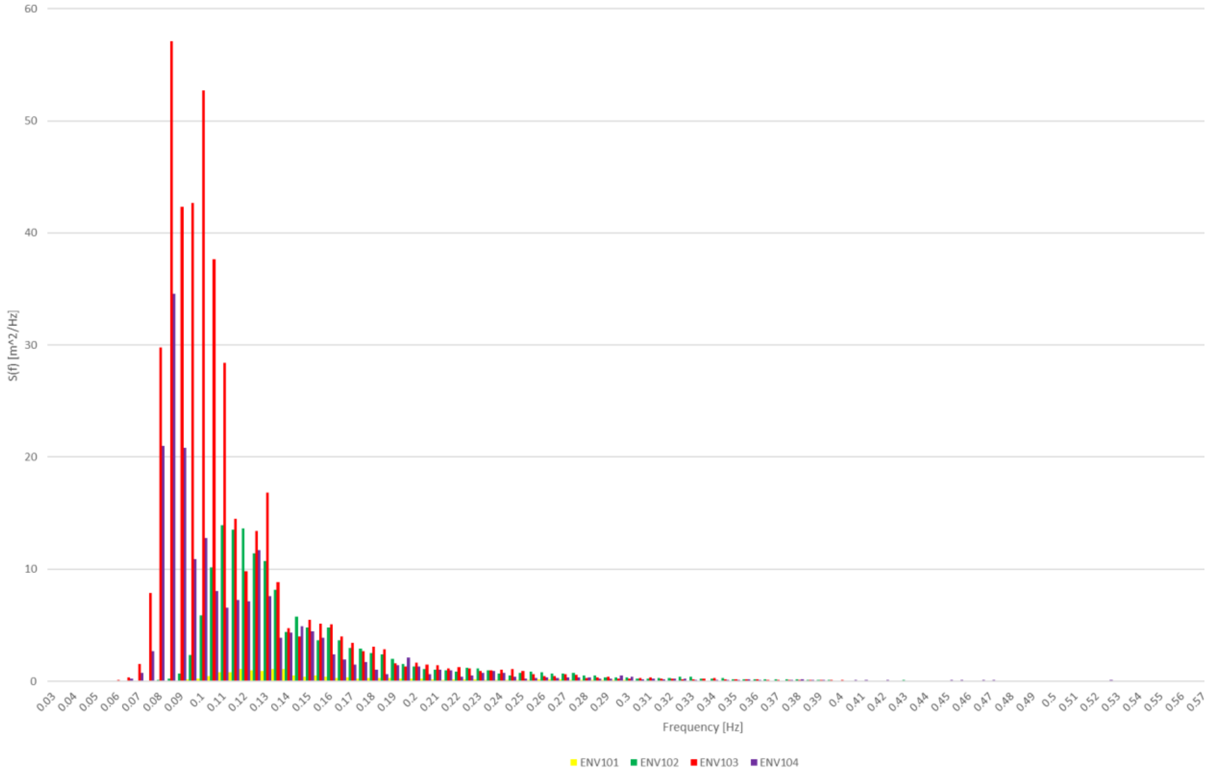


FIGURE. 4-11 TRIAXYS – SPECTRAL ORDINATES

The 4 combinations of waves analysed are summarized in Table. 4-6 below. When inputting the spectral ordinate to Orcaflex, Hs and Tp are not required and are hence greyed out below.

The Triaxys buoy also outputs directional spectral ordinates, these have been input to the two sets of analyses as deterministic spreading using spectral ordinates.

The deterministic spread spectra for ENV103P1 is visualized in Figure. 4-12, with a spreading coefficient, “s” of 9. Full set of directional spectra can be found in Annex H.

In terms of modelling the spreading in Orcaflex the following approach has been taken:

a) The directional spectra from the Triaxys buoy is measured with 3degree increments, to get a reasonable analysis time the increment have been changed to 15deg and the spectra transformed to retain the energy.
b) The deterministic spreading has been modelled using 24 wave headings, each heading defined as a “User Defined Spectrum” with the spectral ordinates from the corresponding heading in the 2D measured spread spectrum.

Method for fitting JONSWAP peakness coefficient “gamma” and the spreading coefficient “s”, is outlined in Annex I.

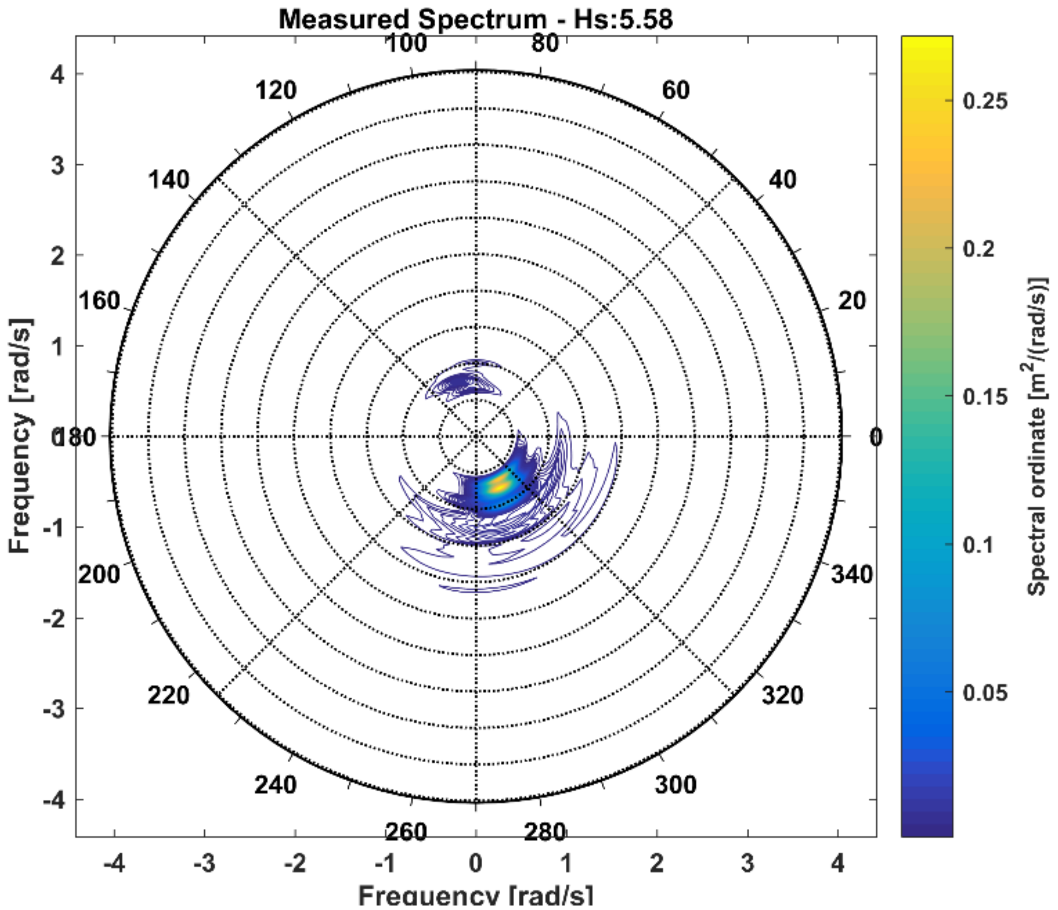


FIGURE. 4-12 DETAILED AND IDEALIZED SPREAD SPECTRA - ENV103P1

TABLE. 4-6 SUMMARY OF APPLIED WAVE ENVIRONMENTS

		Hs [m]	Tp [s]	Spreading Coefficient	Compass Direction* [deg]
Spectral Ordinate	ENV101P1	*1.144*	*7.749*	*Deterministic*	300
	ENV102P1	*3.519*	*8.481*	*Deterministic*	301
	ENV103P1	*5.866*	*10.899*	*Deterministic*	297
	ENV104P1	*4.031*	*11.644*	*Deterministic*	296

Also, there is the Wavescan buoy, operated by BiMEP, that is in proximity to MARMOK. This gave an additional source of wave regime data, see Table. 4-7, plus wind and current data, see Table. 4-8.

TABLE. 4-7 WAVESCAN BUOY – WAVES (HOURLY VALUES)

Code	Hm0 [m]	Hm0 swell [m]	Hm0 sea [m]	Mean spectral direction [deg]	Mean spectral direction swell [deg]	Mean spectral direction sea [deg]	Peak period [s]
ENV101P1	1.094	0.156	1.094	303.8	331.9	305.2	7.121
ENV102P1	1.953	0.156	2.031	302.3	308.0	300.9	5.953
ENV103P1	5.703	3.516	4.531	295.3	295.3	293.9	9.637
ENV104P1	3.984	2.5	3.203	302.3	308.0	298.1	11.883

TABLE. 4-8 WAVESCAN BUOY – WIND AND CURRENT

Code	Curr speed [cm/s]	Current direction - toward [deg]	Wind speed [m/s]	Wind direction [deg]	Wind gust speed [m/s]
ENV101P1	25.195	109.3	2.15	311.5	3.91
ENV102P1	59.77	107.9	16.60	277.7	25.20
ENV103P1	65.04	102.7	16.99	273.5	23.44
ENV104P1	87.60	92.1	13.67	267.2	19.92

The surface current from the Wavescan buoy has been merged with the ADCP data presented in Figure. 4-13, the full 3D current profiles are presented in Figure. 4-13.

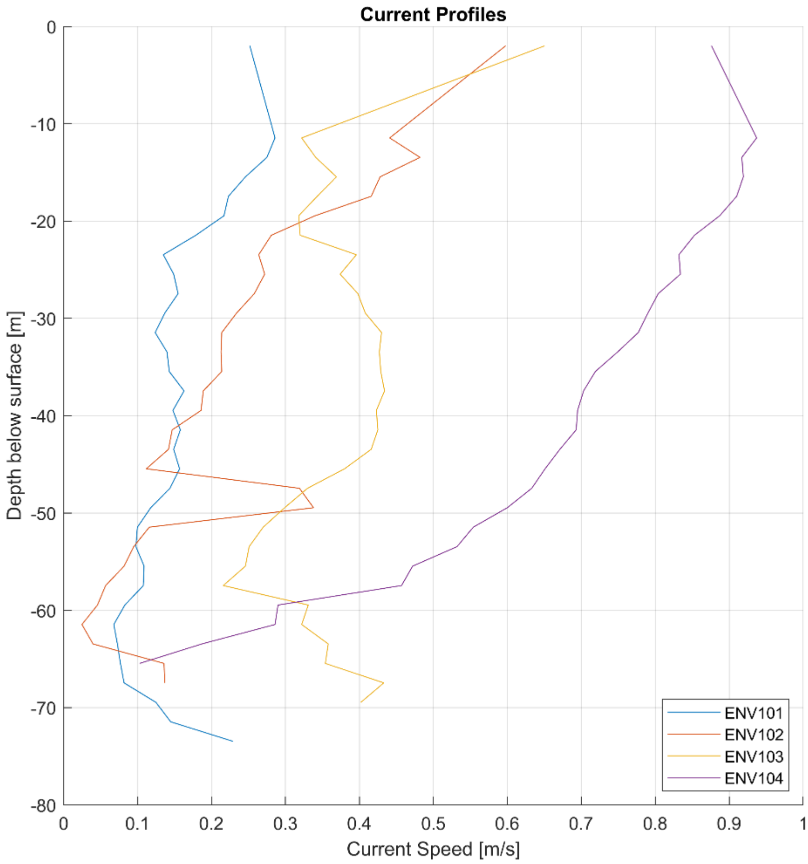


FIGURE. 4-13 CURRENT PROFILES USED FOR ENVIRONMENTS ENV101P1-104P1

The change in water level was obtained from the following weblink: http://www.puertos.es/en-us/oceanografia/Pages/portus.aspx

NB: Since the issue of the report WP2_GM_106_V1 – (47169-2018-02-25), it has been confirmed that the current directions are provide as "going toward" directions.

The tidal rise during the 28/06/17 is presented in Figure. 4-14 and summarised in Table. 4-9.

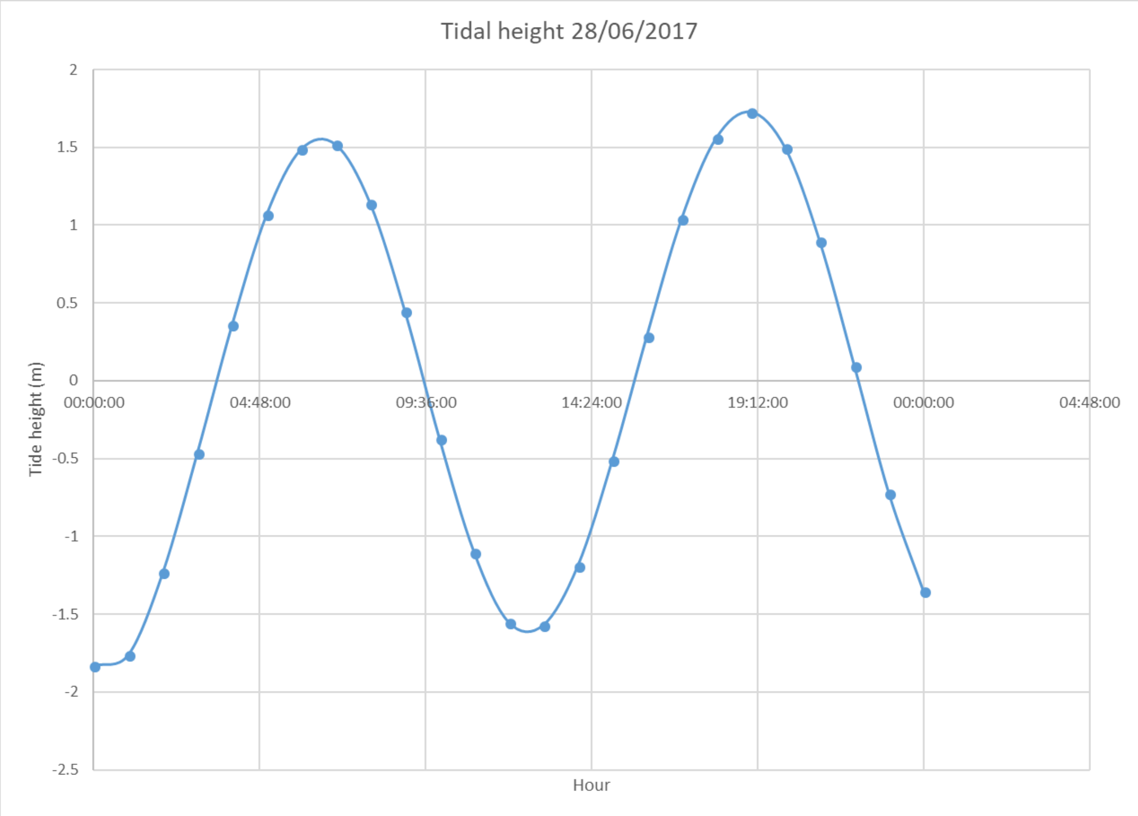


FIGURE. 4-14 TIDAL CHANGE ON 28/06/2017

The environment directions as applied in Orcaflex, in the sense “going toward”, are presented in Table. 4-9, full current profile directions are listed in section 16. In Orcaflex 0 deg is +ve along the X-direction outwards (towards East), 90 deg is +ve along the Y-direction outwards (towards North).

TABLE. 4-9 ENVIRONMENT DIRECTIONS IN ORCAFLEX FOR P1

Code	Wave	Surface Current	Wind	Tide [m]
ENV101P1	-30.0	-19.3	-41.5	-1.55
ENV102P1	-31.0	-17.9	-7.7	0.29
ENV103P1	-27.0	-12.7	-3.5	1.50
ENV104P1	-26.0	-2.1	2.8	-1.31

5. VALIDATION OF MARMOK MEASURED MOTIONS AND MOORING LINE LOADS

This section presents the aspects of the validation of the numerical model of the moored MARMOK wave energy converter. The aspects that are summarised include:

- Motion response
- Mooring load response
- Uncertainties in the validation parameters

For the purposes of the validation three distinct environmental situations have been used:

i. Low environment on the 6/05/17 for P1 and 30/12/2018 for P2
ii. Medium environment on the 28/06/17 for P1 and 23/12/2018 for P2
iii. Extreme environment of the 28/06/17 for P1 and 14/12/2018 for P2

The validation process focusses on the following parameters:

- Surge and sway of the radar antenna
- Heave at the CoG
- Roll and Pitch of the MARMOK
- Tension at the upper end of the catenary of Line #1

The results presented in here are an update of the results presented in WP2_GM_108, where detailed current profile from an ADCP has been included in the Orcaflex model. Moreover, the MARMOK added mass and drag has been updated; and a 6% permanent elongation of the polyester lines has been assumed.

As the anchor depths for the four mooring lines vary, this introduces asymmetries into the mooring system. This contributes to the static equilibrium position of the MARMOK model to be non-zero under null environment.

To get the same mean roll and pitch in OrcaFlex as for the measured data in the small environment, the OrcaFlex lateral cog has been shifted. The cog has been shifted such that the static heel and trim is the same as the mean roll and pitch in the measured small environment. The updated cog and corresponding incline is presented in Table. 5-1.

TABLE. 5-1 COG SHIFT (LOCAL COORDINATE SYSTEM)

	TCG [m]	**LCG [m]**
Orcaflex COG	-0.0748	-0.0125
	Heel [deg]	**Trim [deg]**
Orcaflex	-0.514	-0.767
Site Measured	-0.516	-0.760

Consequently, the static equilibrium of the MARMOK has shifted and the static equilibrium coordinates (COG) from the Orcaflex model of the MARMOK are:

- -1.262m east (X coord.), 5.861m north (Y coord.)

5.1 MEASURED POSITION

A fix on the UTM coordinates of the DGPS antenna on the MARMOK were taken shortly after installation in October 2016. These are recorded as:

- UTM coordinate: 510530.5 east, 4812946 north, UTM zone 30T
- Latitude 43.4693deg Long -2.8698 deg

Even under low environment (ENV000P1 and ENV000P2), there is a small but measurable oscillation of the DGPS antenna about the UTM fix, see Figure. 5-1. The oscillation is about 200cm range for Easting and 150m for Northing.

The results presented here in have been "zeroed"; Orcaflex results has been zeroed using static equilibrium without environment; and the measured data have been zeroed using the "small environment" mean position.

Note that all results presented in the body of this report is using the deterministic spreading.

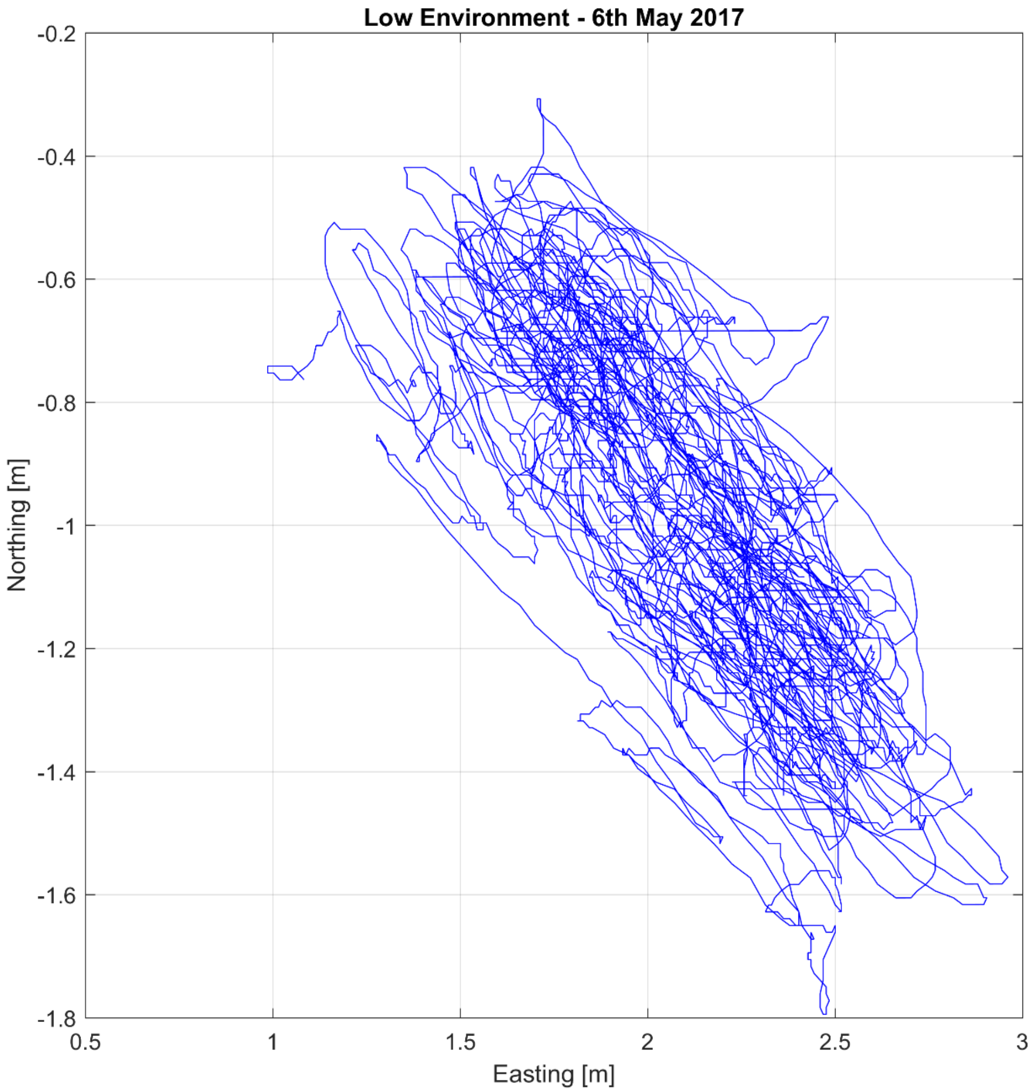


FIGURE. 5-1 LOW ENVIRONMENT - ENV000 – DGPS POSITION

5.2 POLYESTER PERMANENT SET

The mooring line manufacturer has stated that the polyester lines can experience up to 6% permanent elongation. The results presented for ENV101-104 herein are based on the Cadena and Conex lines extended by 6%. To keep the weight and buoyancy consistent, diameter and weight per unit length has been updated.

5.3 MARMOK ADDED MASS AND DRAG

The added mass and drag of the MARMOK has been updated compared to WP2_GM_107_v1, so that the normal added mass coefficient is 1 for the entire length of the MARMOK. The normal drag has been set to be Reynolds number dependent. Reynolds number dependent drag from has been digitized and input to Orcaflex, see Figure 13. Note that it has been assumed that the MARMOK surface is rough.

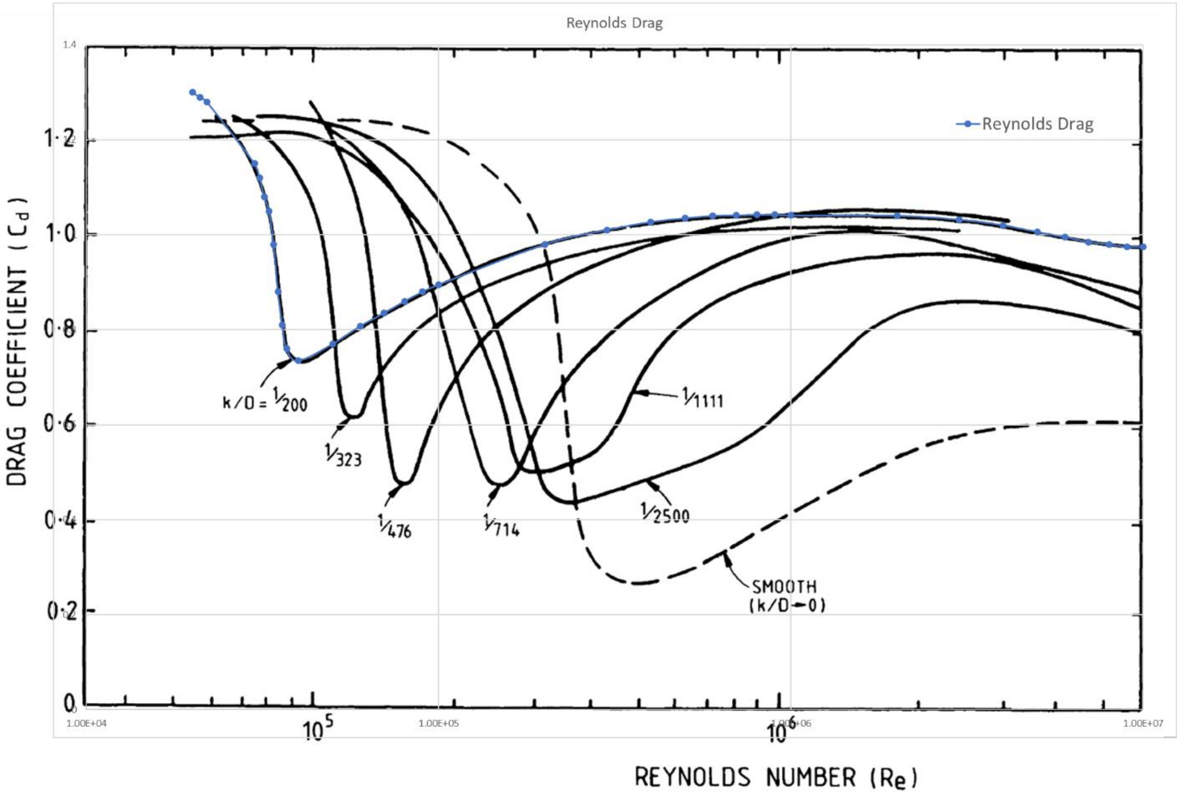


FIGURE. 5-2 REYNOLDS NUMBER DEPENDENT DRAG

5.4 MARMOK MOTION

5.4.1 PHASE 1

5.4.1.1 MEAN POSITION AND FOOTPRINTS

This section aims to demonstrate that the environment directions as received and presented in the previous section have been applied correctly in the numerical (OrcaFlex) model.

The corresponding environment directions as applied in the analyses and post-processed results are again displayed in

Figure. 5-3 and section 9 and 10 present this information for all environments. A summary of the Easting and Northing comparisons is presented in Table. 5-2 for all environments of P1.

TABLE. 5-2 DGPS EXCURSION – MEAN - P1

Environment	Easting (m)			Northing (m)		
	Measured	Analysed	Difference [m]	Measured	Analysed	Difference [m]
ENV000P1	0.00	0.25	-1.01	0.00	-0.02	5.84
ENV101P1	6.00	5.54	-0.46	1.43	3.52	2.09
ENV102P1	13.68	13.38	-0.30	0.52	0.68	0.16
ENV103P1	17.37	14.92	-2.45	1.17	3.64	2.47
ENV104P1	25.56	23.22	-2.34	10.51	10.91	0.40

Analysis - used wave spectral ordinates

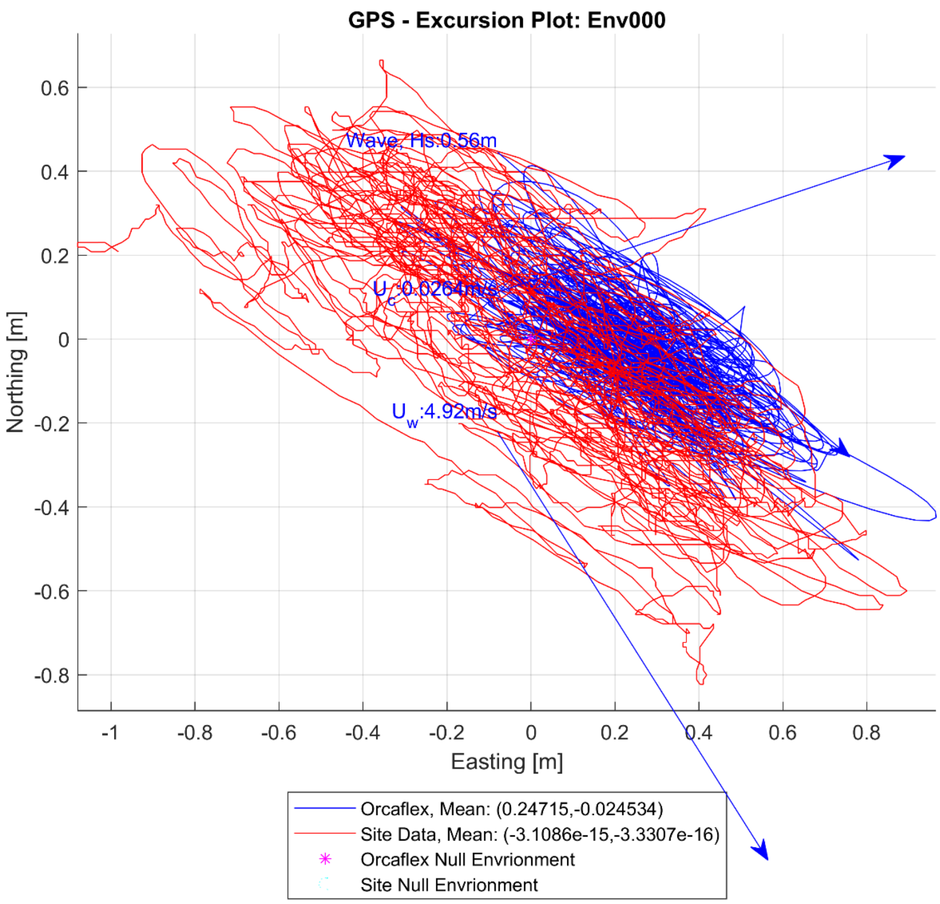


FIGURE. 5-3 LOW ENVIRONMENT FOR PHASE 1 – RADAR ANTENNAE POSITION

This comparison is improved compared with report WP2_GM_108_v1, due to the permanent set and updated added mass & drag. There still is some difference in mean Easting and Northing, it is not known what this difference is due to i.e. the measured mean position indicate that the MARMOK is going further East and going less to North than the numerical model.

5.4.1.2 MOTION TIME SERIES

The motion time series for ENV103P1 which is part of the storm with largest Hs, are presented in Figure. 5-4.

Northing and Easting The Northing and Easting are the same data as presented in

Figure. 5-3 and section 10. A summary of the motion standard deviations in the Easting and Northing directions is presented in Table. 5-3 for all environments.

TABLE. 5-3 DGPS EXCURSION PHASE 1- STD DEV

Environment	Easting [m]			Northing [m]		
	Measured	Analysed	% Difference	Measured	Analysed	% Difference
ENV000P1	0.34	0.19	-45%	0.28	0.14	-51%
ENV101P1	0.40	0.56	37%	0.44	0.69	56%
ENV102P1	1.70	1.62	-5%	1.35	1.94	44%
ENV103P1	2.94	2.51	-15%	2.56	2.45	-4%
ENV104P1	1.37	1.37	0%	2.24	1.22	-46%

Comparison of the measured and analysed Easting and Northing standard deviation of motion are reasonably good, particularly the Easting. The differences between measured and analysed motions are more distinct in the Northing direction. Figure. 5-5 is an example of the ENV103P1 comparison. In Table. 5-5Figure. 5-6 and Figure. 5-7 is observed that the analysed and measured motions (mean and standard deviation) follow similar trends, particularly in Easting.

Heave A summary of the motion standard deviations in Heave at the COG is presented in Figure. 5-8 and Table. 5-4. This shows that there is generally good similarity on the heave standard deviation between measured and analysis. However, there is an increasing difference in mean heave with increasing environment severity, this may be due to the increased mean pressure in the MARMOK internal chamber.

TABLE. 5-4 COG HEAVE – ST DEV

Environment	Std Dev [m]		
	Measured	Analysed	% Difference
ENV000P1	0.26	0.38	47%
ENV101P1	0.37	0.70	89%
ENV102P1	1.25	1.54	23%
ENV103P1	2.29	2.02	-12%
ENV104P1	1.26	1.46	16%

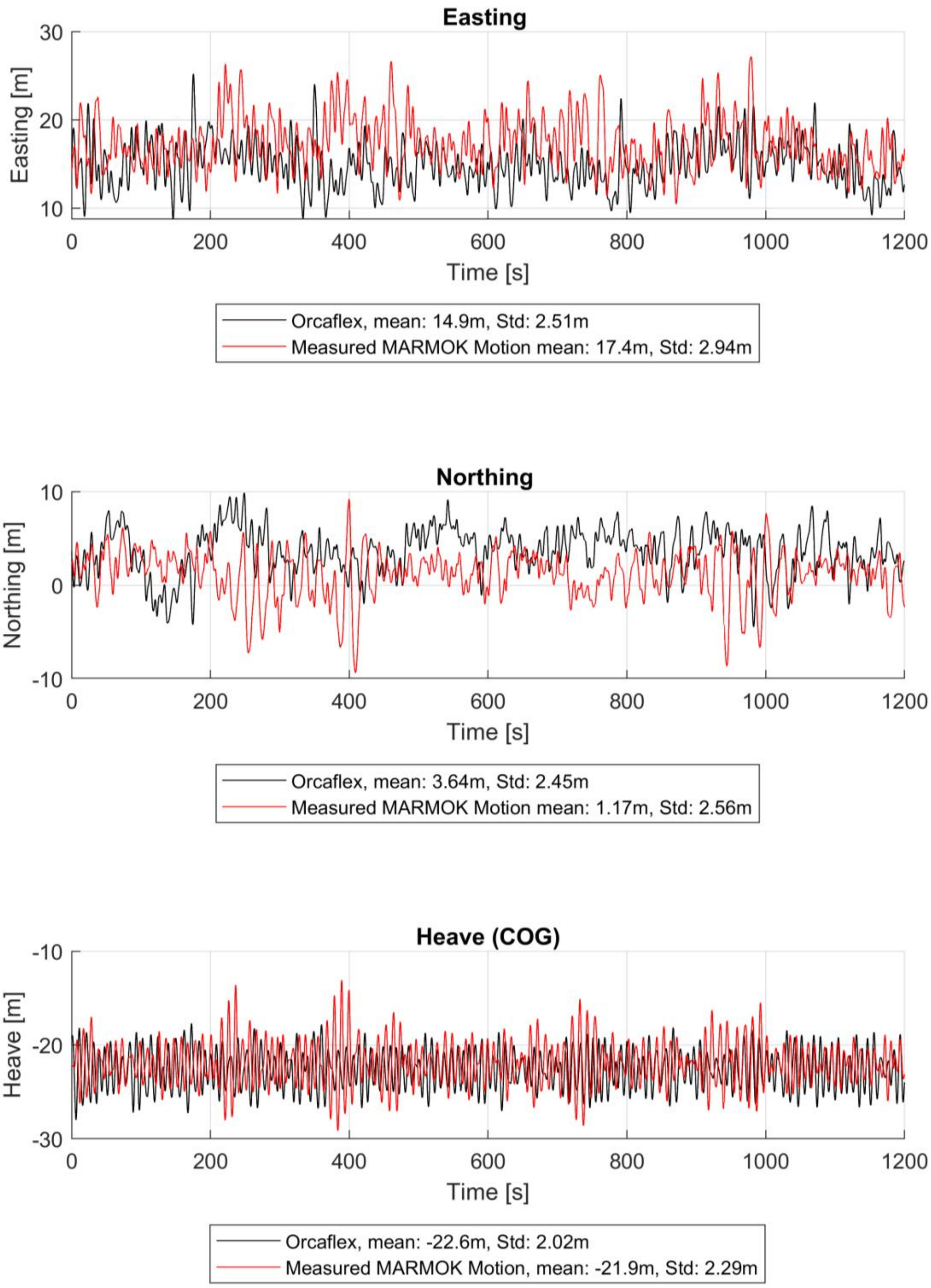


FIGURE. 5-4 TIME SERIES OF EASTING, NORTHING AND HEAVE FOR ENV103P1

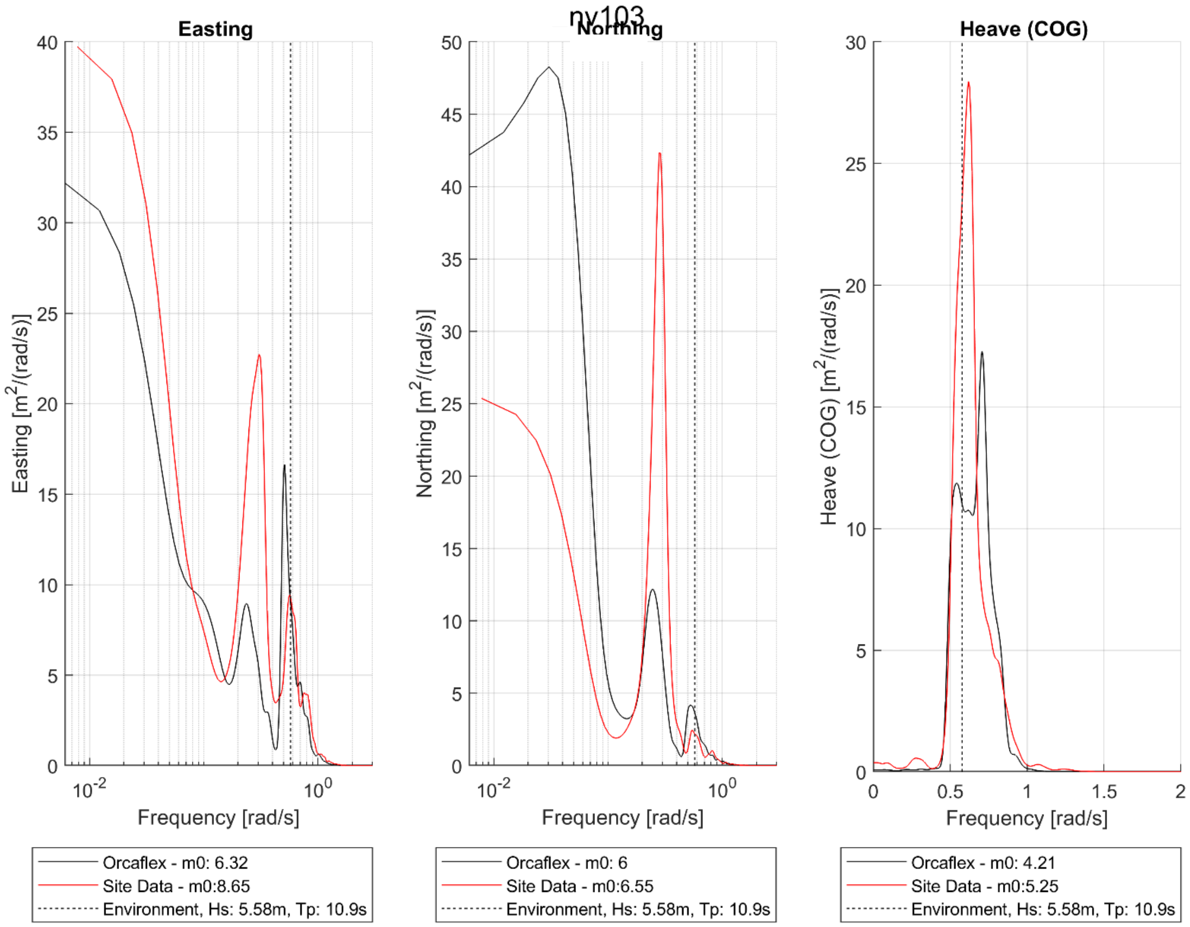


FIGURE. 5-5 ENV103P1 – MEASURED AND PREDICTED MOTION SPECTRA– EASTING, NORTHING AND HEAVE

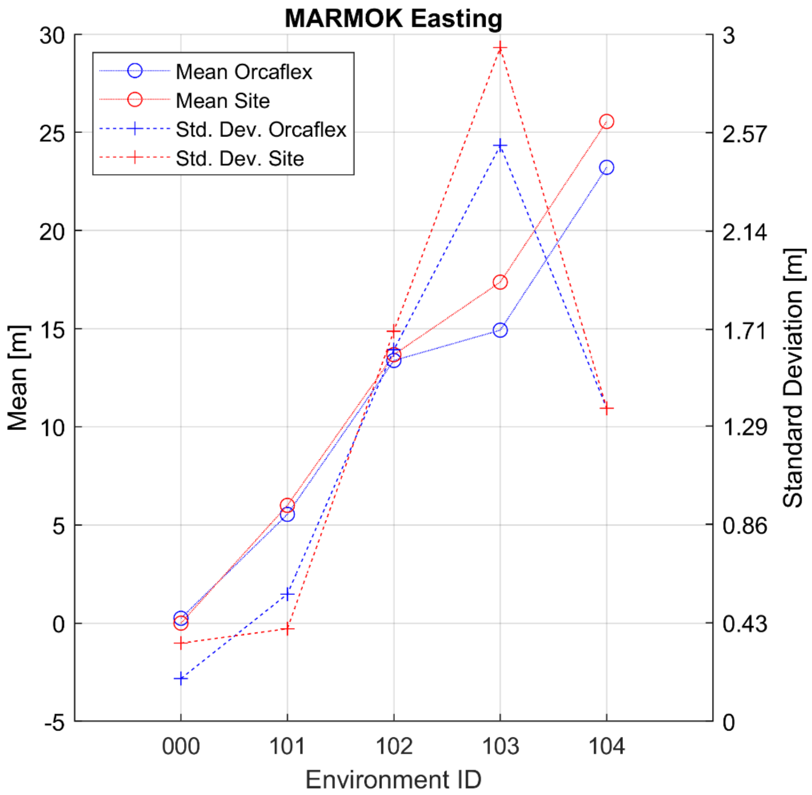


FIGURE. 5-6 MARMOK EASTING: MEAN AND STANDARD DEVIATION BY ENVIRONMENT – PHASE 1

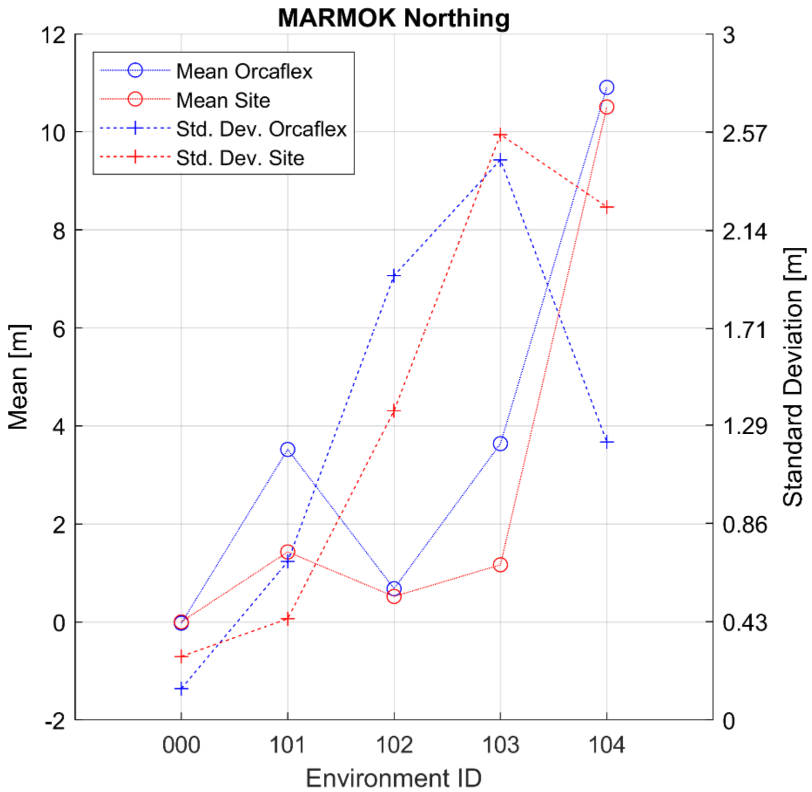


FIGURE. 5-7 MARMOK NORTHING: MEAN AND STANDARD DEVIATION BY ENVIRONMENT – PHASE 1

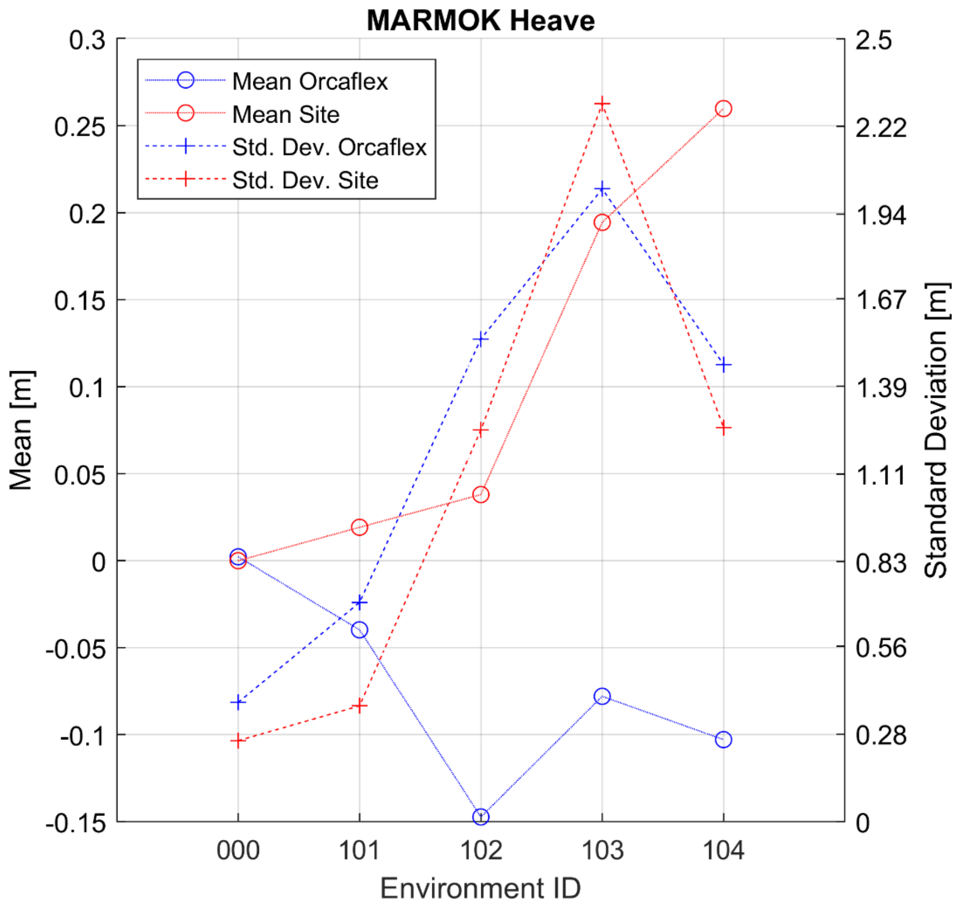


FIGURE. 5-8 MARMOK HEAVE: MEAN AND STANDARD DEVIATION BY ENVIRONMENT – PHASE 1

5.4.1.3 ROLL AND PITCH

In report WP2_GM_107_v1 it was noted that the measured data had an underlying heel and pitch. To account for this the Orcaflex model COG have been shifted so that the measured mean roll and pitch from the small environment is the same as the static heel and trim.

The mean and standard deviation of the roll and pitch for all the environments are presented in Table. 5-5 and Table. 5-6.

The time trace and spectral energy plot of the roll and pitch motions for ENV103P1 are presented in Figure. 5-9. It is quite apparent that there is very little roll predicted from the analysis. 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. plane of pitch in 131deg direction) of the MARMOK, being almost parallel. It is not clear what is the cause of the measured roll motion.

Mean and standard deviations are plotted in Fig. 5-11 and. The site measured mean Roll and Pitch appear to have a significantly larger heel and trim than the analysed, that cannot be accounted for by the eccentric lateral position of the centre of gravity. Some of the difference in mean roll/pitch may come from the difference in mean heave/draught which affects the VCB which would affect the GM_T i.e. the restoring stiffness.

Particularly dramatic differences are observed for ENV104 for mean of Roll and Pitch, and standard deviation of Roll. The cause of this is not clear.

TABLE. 5-5 PITCH - PHASE 1

Environment	Mean [deg]			Std Dev [deg]		
	Measured	Analysed	Difference [deg]	Measured	Analysed	% Difference
ENV000P1	-0.52	0.12	0.63	0.13	0.09	-29%
ENV101P1	0.77	0.33	-0.44	0.25	0.35	41%
ENV102P1	0.80	0.09	-0.71	1.00	1.27	28%
ENV103P1	1.03	0.29	-0.74	5.03	2.18	-57%
ENV104P1	2.21	2.33	0.12	2.94	1.18	-60%

Analysis - used wave spectral ordinates

TABLE. 5-6 ROLL - PHASE 1

Environment	Mean [deg]			Std Dev [deg]		
	Measured	Analysed	Difference [deg]	Measured	Analysed	% Difference
ENV000P1	-0.76	-0.87	-0.11	0.27	0.27	1%
ENV101P1	-1.03	-0.82	0.20	0.49	0.51	5%
ENV102P1	-0.45	0.51	0.95	2.76	2.39	-13%
ENV103P1	-0.11	0.43	0.54	4.64	3.66	-21%
ENV104P1	-3.24	-2.91	0.34	2.95	2.17	-26%

Analysis - used wave spectral ordinates

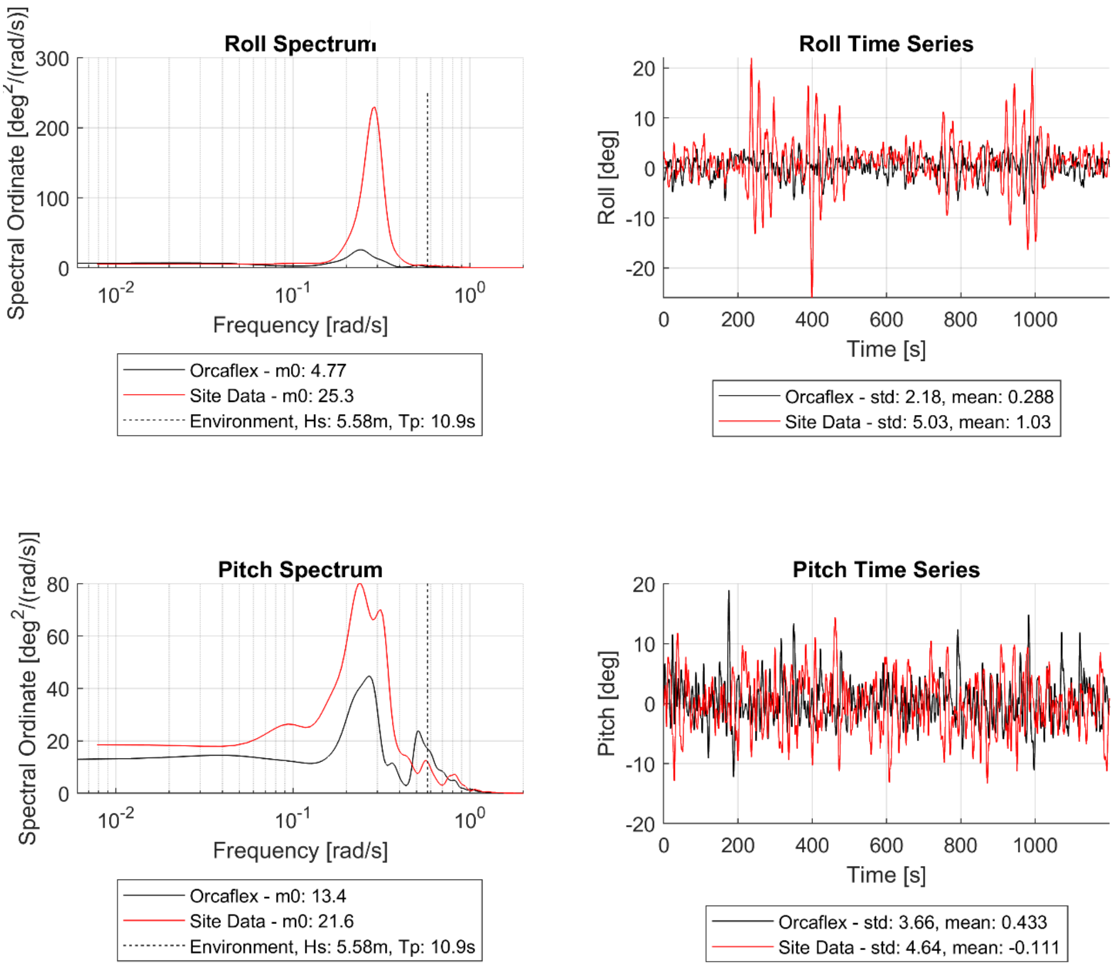


FIGURE. 5-9 ENV103 – TIME SERIES OF ROLL, PITCH AND HEAVE - P1

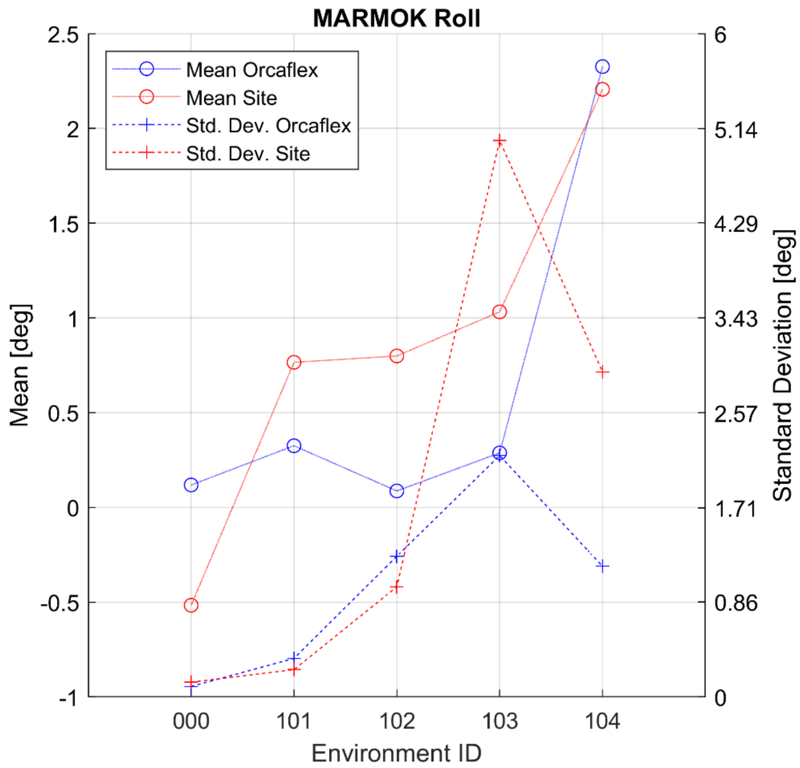


FIGURE. 5-10 MARMOK ROLL MEAN AND STANDARD DEVIATION - P1

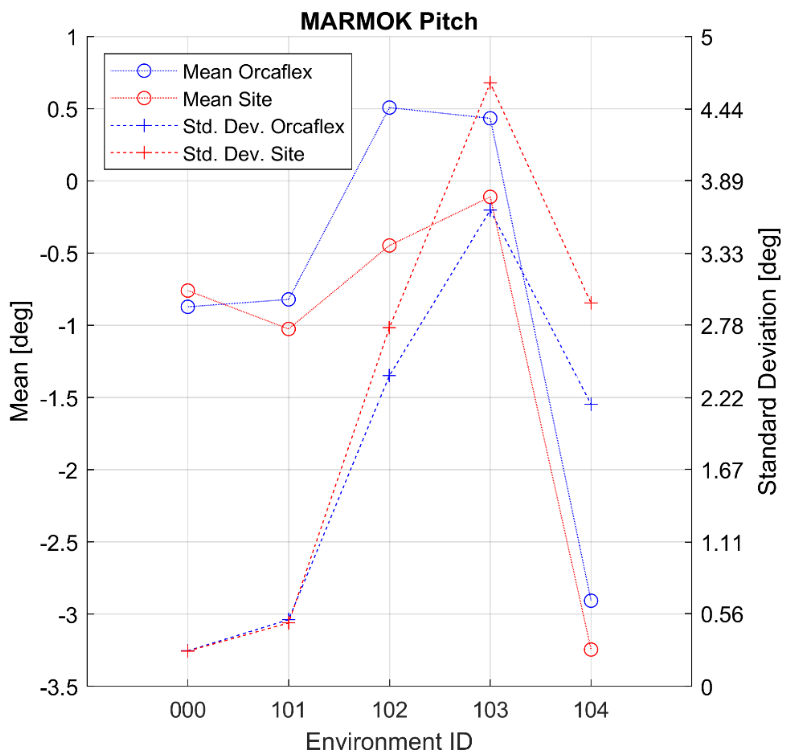


FIGURE. 5-11 MARMOK PITCH MEAN AND STANDARD DEVIATION - P1

5.4.2 **PHASE 2**

5.4.2.1 **MEAN POSITION AND FOOTPRINTS**

This section aims to demonstrate that the environment directions as received and presented in Phase 2 have been applied correctly in the numerical (OrcaFlex) model.

The corresponding environment conditions as applied in the analyses and post-processed results are presented in Section 4. A comparison of results from measurements and OrcaFlex results for Radar Antenna Position for horizontal motion (Northing vs Easting) are shown in Figure 5-13.

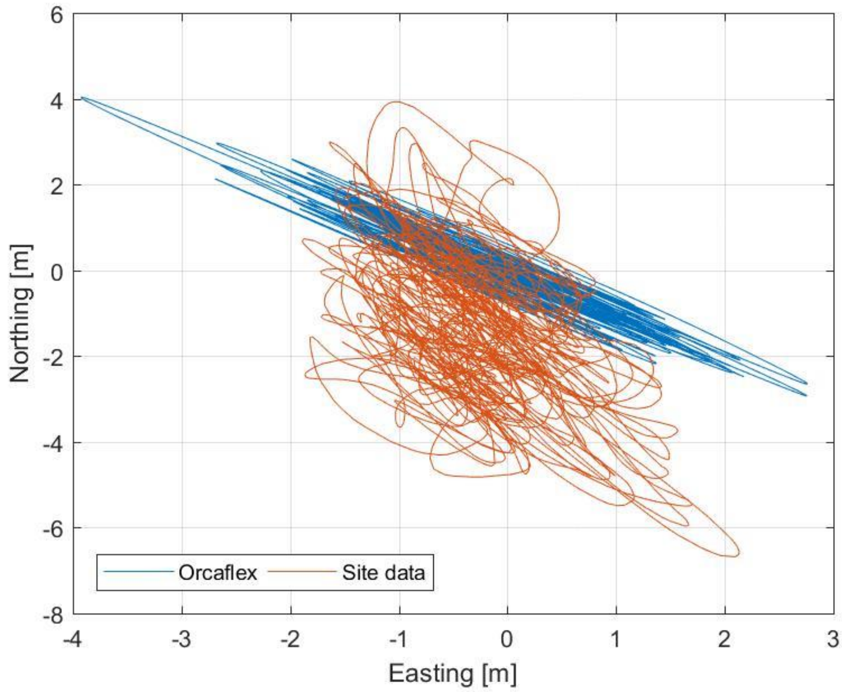


FIGURE. 5-12 LOW ENVIRONMENT FOR PHASE 2 – RADAR ANTENNAE POSITION

5.4.2.2 **MOTION TIME SERIES**

The Northing and Easting are the same data as presented in Figure. 5-14 for Phase 2 deployment and section 10. A summary of the motion standard deviations in the Easting and

Northing directions are tabulated in Table. 5-7 and Table. 5-8, respectively, for all environments in Phase 2 deployment.

TABLE. 5-7 EASTING - PHASE 2

	Mean			Standard Deviation		
Environment	Measured	Analysed	Difference	Measured	Analysed	% difference
Low	0.074	-0.008	-0.082	0.101	0.115	13.2
Medium	-0.672	-0.011	0.661	0.302	0.430	42.4
Extreme	-0.305	-0.148	0.157	0.649	0.997	53.7

TABLE. 5-8 NORTHING – PHASE 2

	Mean			Standard Deviation		
Environment	Measured	Analysed	Difference	Measured	Analysed	% difference
Low	-0.260	-0.042	0.218	1.631	0.073	95.6
Medium	0.107	0.090	-0.017	0.469	0.295	37.1
Extreme	-1.334	0.273	1.607	1.631	1.071	34.3

Furthermore, a summary of the Easting and Northing is presented in Figure. 5-14 and Figure. 5-15, respectively, for all environments in Phase 2 deployment.

For the heave time series at the COG in Figure. 5-16, summary of the motion standard deviations is presented in Table. 5-9. This shows that there is generally good similarity on the heave standard deviation between measured and analysed data.

TABLE. 5-9 HEAVE – PHASE 2

	Mean			Standard Deviation		
Environment	Measured	Analysed	Difference	Measured	Analysed	% difference
Low	-0.00059	-0.0015	-0.0009	0.241	0.345	43.2
Medium	-0.00116	-0.0114	-0.0102	0.600	0.681	13.4
Extreme	0.00071	0.0759	0.0751	0.946	1.350	42.6

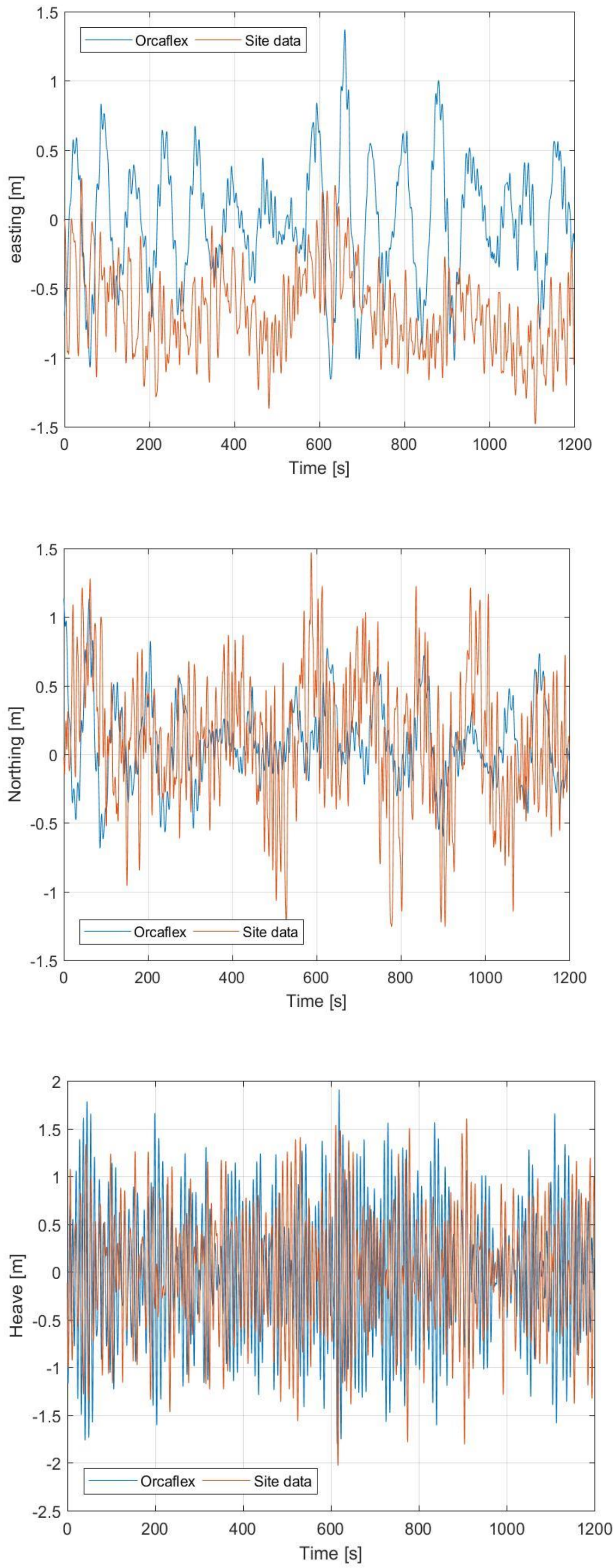


FIGURE. 5-13 TIME SERIES OF EASTING, NORTHING AND HEAVE FOR ENV103P2

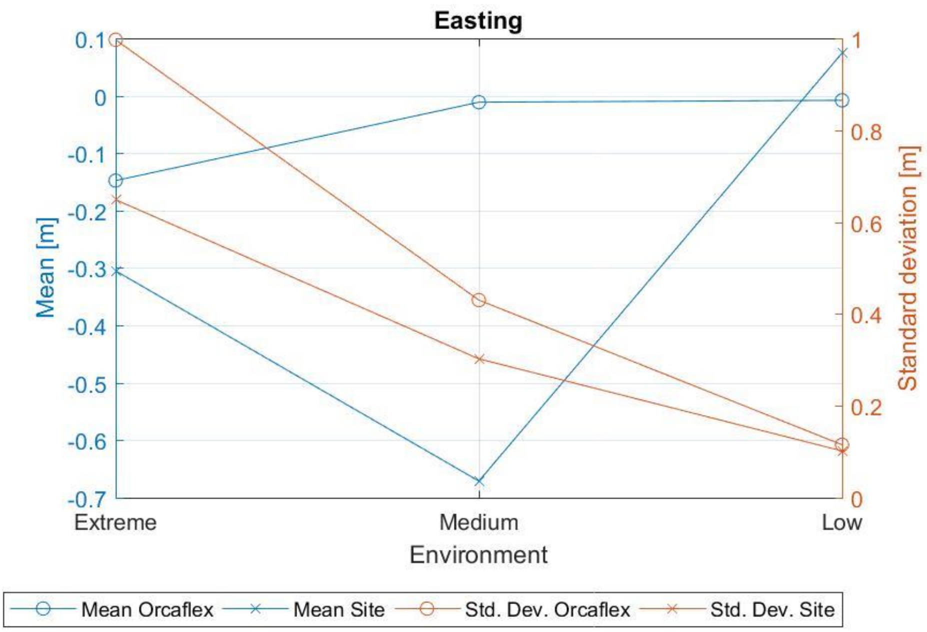


FIGURE. 5-14 MARMOK EASTING: MEAN AND STANDARD DEVIATION BY ENVIRONMENT – PHASE 2

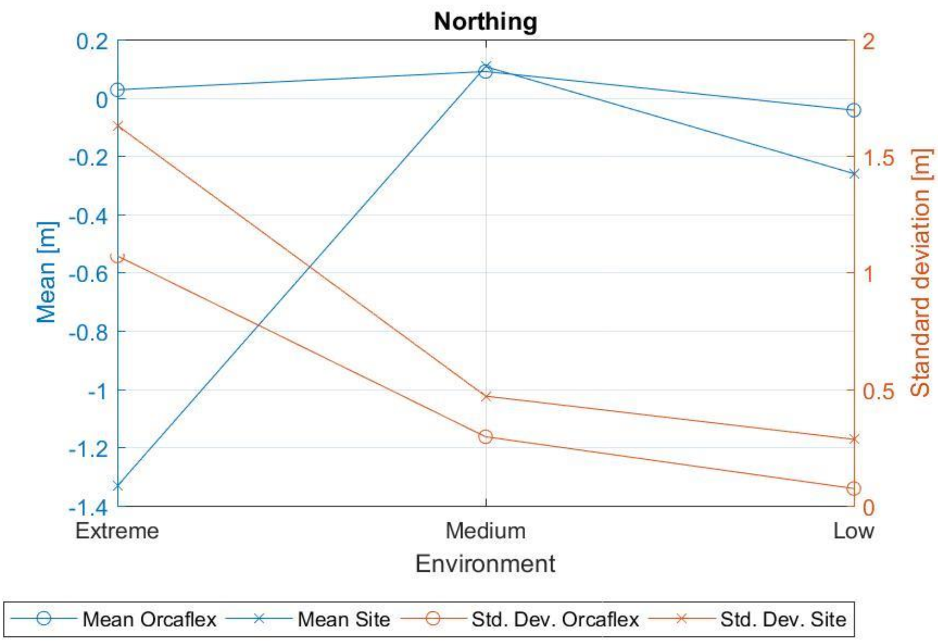


FIGURE. 5-15 MARMOK NORTHING: MEAN AND STANDARD DEVIATION BY ENVIRONMENT - PHASE 2

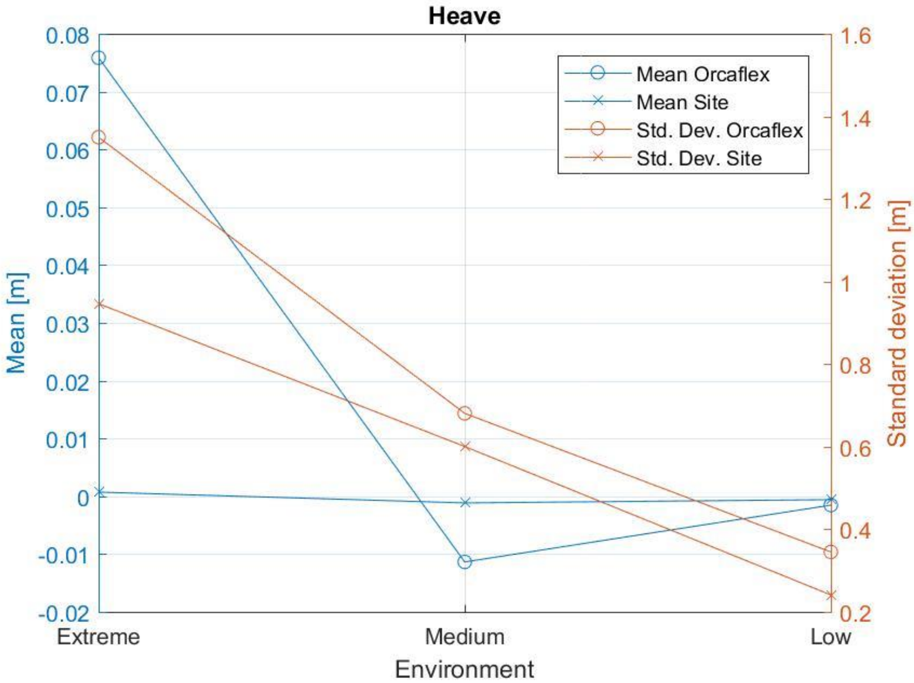


FIGURE. 5-16 MARMOK HEAVE: MEAN AND STANDARD DEVIATION BY ENVIRONMENT – PHASE 2

5.4.2.3 ROLL AND PITCH

The time trace and spectral energy plot of the roll and pitch motions for ENV103P1 are presented in Figure 5-17. The spectra and time trace for the remaining environments for P2 deployment can be found in section 12 for comparison.

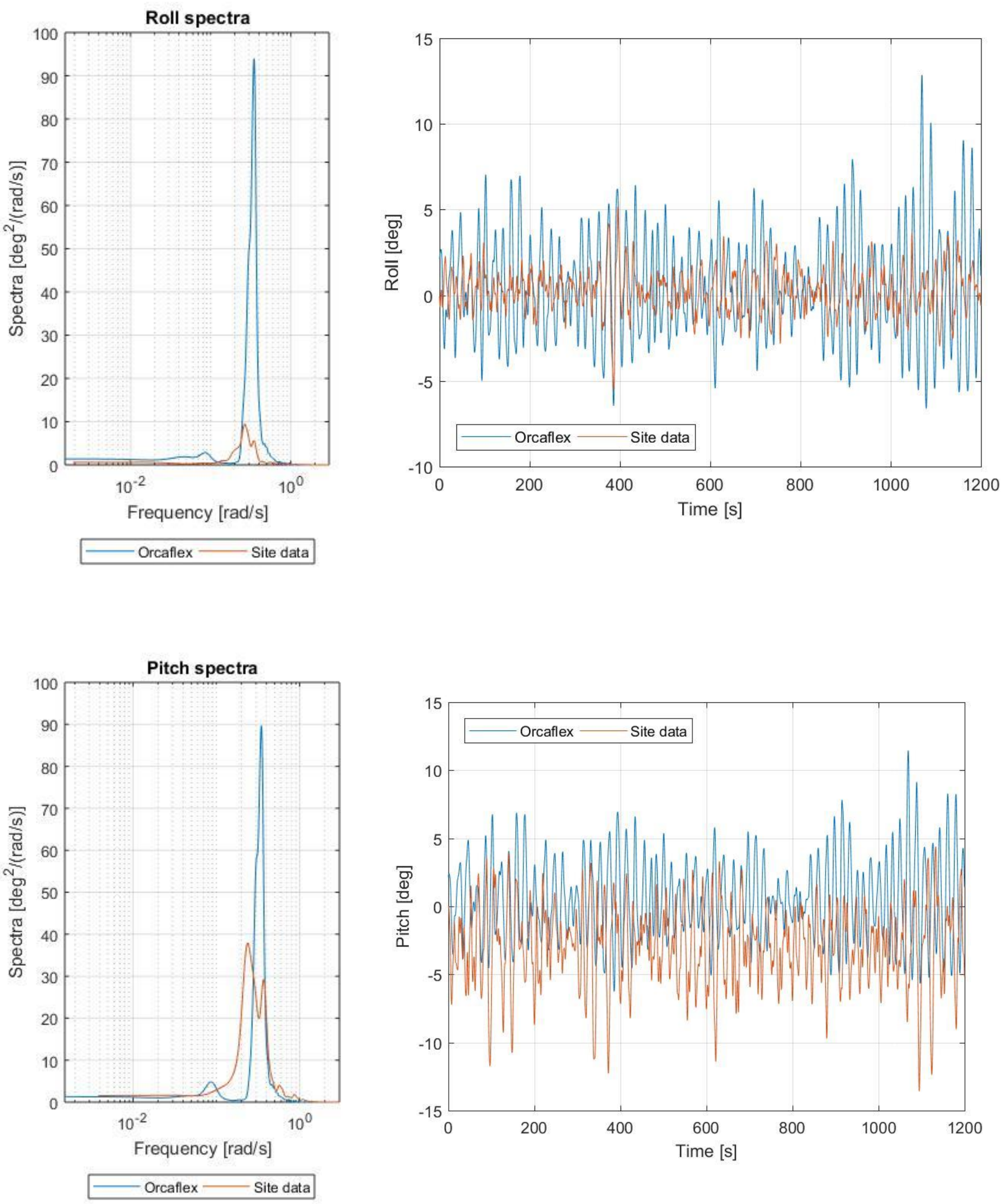


FIGURE. 5-17 ROLL AND PITCH SPECTRA AND TIME SERIES FOR ENV103P2

5.5 MARMOK TENSION RESPONSE – CADENA LINE

5.5.1 PHASE 1

The time trace and spectral energy of the line tension for Cadena 1 under ENV103P1 are presented in Figure. 5-18. The mean and standard deviation of the tension for all the environments are presented in Table. 5-10 and Figure. 5-19. The analysed mean tension is somewhat larger than the measured value for ENV102 & ENV104. The analysed standard deviation is generally smaller (except ENV102) compared to the measured standard deviations. These differences are related to the observed differences between measured and analysed: position, motions, heave, roll and pitch.

Nevertheless, this comparison is greatly improved compared with report WP2_GM_108_v1, due to the inclusion of permanent set and improved added mass & drag.

TABLE. 5-10 ENV103P1 – CADENA TENSIONS

Environment	Mean [kN]			Std Dev [kN]		
	Measured	Analysed	% Difference	Measured	Analysed	% Difference
ENV000	23.14	24.75	7%	1.77	0.41	-77%
ENV101	21.96	18.40	-16%	2.61	1.94	-26%
ENV102	36.73	39.04	6%	7.31	7.35	0%
ENV103	45.67	44.58	-2%	18.89	10.66	-44%
ENV104	69.44	76.30	10%	26.37	17.81	-32%

Analysis - used wave spectral ordinates

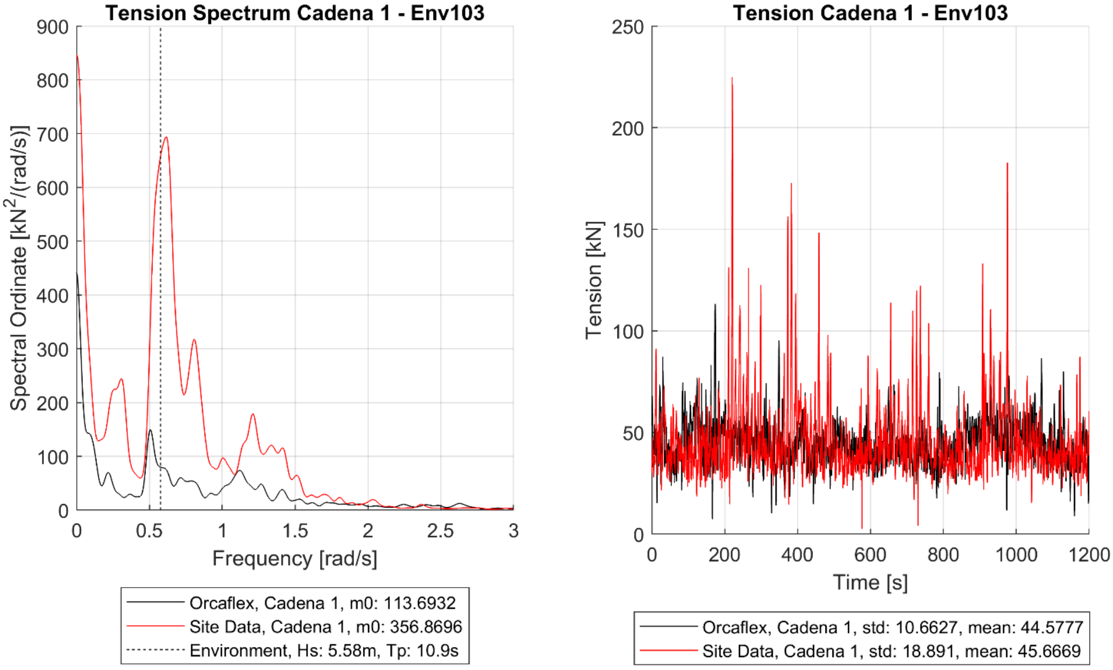


FIGURE. 5-18 ENV103P1 – CADENA TENSION

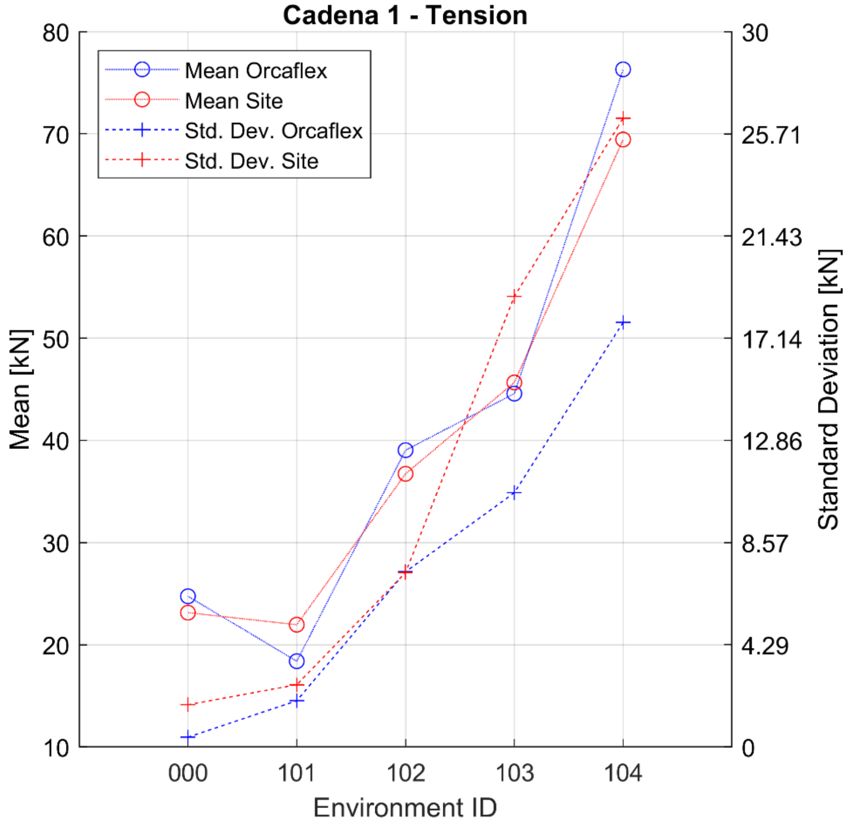


FIGURE. 5-19 CADENA 1 TENSION – MEAN AND STANDARD DEVIATION – PHASE 1

5.5.2 PHASE 2

The time trace and spectral energy of the line tension for Cadena 1 under ENV103P2 are presented in

Figure. 5-20. The mean and standard deviation of the tension for all the environments are presented in Table. 5-11 and Figure. 5-21. The analysed mean tension is somewhat larger than the measured value for the extreme environment, namely ENV103P1. The analysed standard deviation is smaller for ENV103P1 compared to the measured standard deviations. These differences are related to the observed differences between measured and analysed: position, motions, heave, roll and pitch.

TABLE. 5-11 MEAN AND STANDARD DEVIATION FOR THE ENVIRONMENTS IN PHASE 2 DEPLOYMENT

	Mean [kN]			Standard Deviation [kN]		
Environment	Measured	Analysed	% Difference	Measured	Analysed	% Difference
Low	39.56892	38.80849	-1.92	0.45	0.608208	34.29
Medium	39.76476	38.77	-2.50	1.458473	1.795962	23.13
Extreme	56.22923	67.04532	19.23	12.9471	11.74702	-9.27

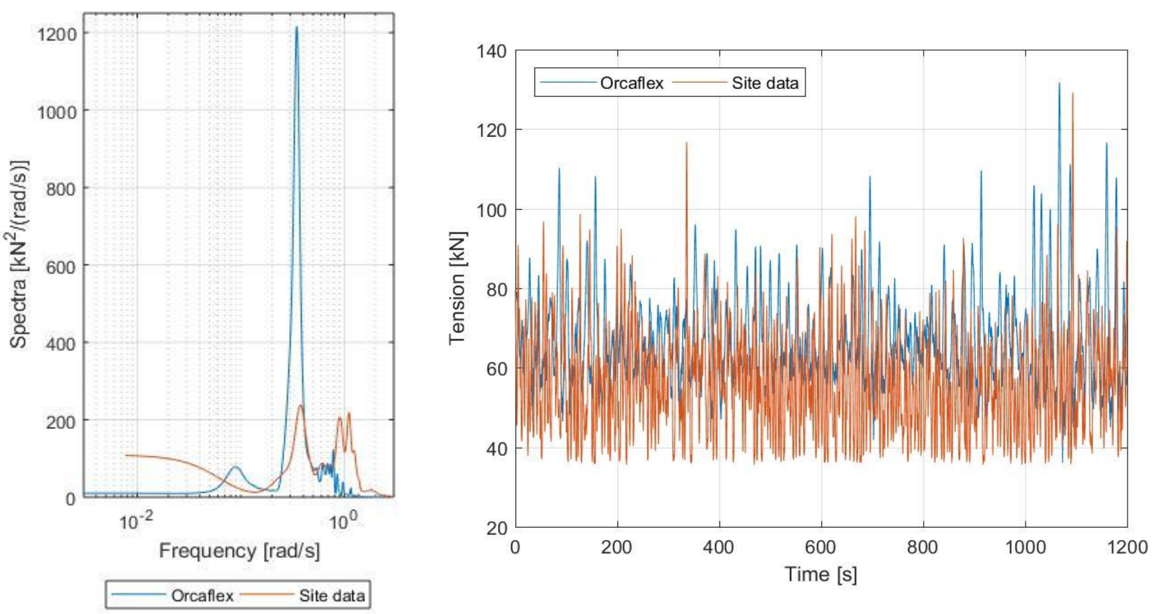


FIGURE. 5-20 ENV103P2 – CADENA TENSION

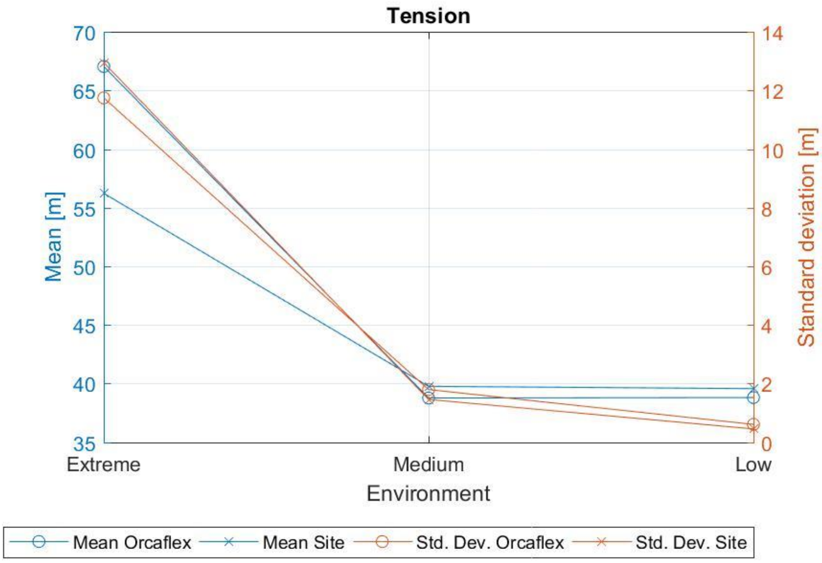


FIGURE. 5-21 CADENA 1 TENSION – MEAN AND STANDARD DEVIATION – PHASE 2

6. COMPARISON OF DEPLOYMENT P1 AND P2

This chapter presents a comparison of the two investigated deployment phases, Phase1 and Phase 2. The comparative study of the two deployment phases is conducted using low, medium and extreme environmental conditions with similar, but not identical, environmental conditions. The environmental conditions that occurred during Phase 1 and Phase 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.

The chapter provides a comparison between Phase 1 and Phase 2 presenting: i) overview of the environmental conditions applied for the comparison study, ii) results from horizontal motion in Radar Antenna Position for horizontal motion (Northing vs Easting), iii) Heave motion, iv) Roll and Pitch motion and v) tension characteristics.

KEY FINDINGS:

- 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.

6.1 ENVIRONMENTAL CONDITIONS

The environmental conditions are applied for the comparison study are discussed in more detail in chapter 4. No direct comparable environmental conditions were measured between Phase 1 and Phase 2 and hence conditions were chosen that were similar. The environment conditions applied for comparison between Phase 1 and Phase 2 are presented in Table 6-1.

TABLE. 6-1 ENVIRONMENTAL CONDITIONS FOR PHASE 1 AND PHASE 2 COMPARISONM

	Low Environment		Medium Environment		Extreme Environment	
	Phase 1 (06/05/2017, 10:00:00)	Phase 2 (30/12/2018 13:00:00)	Phase 1 (28/06/2017 at 12:00:00)	Phase 2 (23/12/2018 at 14:00:00)	Phase 1 (28/06/2017 20:00:00)	Phase 2 (14/12/2018 11:00:00)
Hs (m)	0.56	0.58	1.06	1.17	5.58	4.6
Tp (s)	11	11.16	8.3	9.1	11.8	16.02
Direction (°)	303	324.84	300	308	297	312.19

6.2 EASTING AND NORTHING

The maxima and minima motion results were obtained from graphs in Figure 6-3. The readings were used to obtain the range of motion in Easting (Table 6-2) and Northing (Table 6-3) for the three environmental conditions for both, Phase 1 and Phase 2. The results for Easting and Northing are graphically presented in figure 6-1 and 6-2, respectively. It can be observed that a motion range is decreasing in Phase 2 for extreme environmental condition.

TABLE. 6-2 EXTREME VALUES AND RANGE FOR THE MARMOK EASTING

Environmental conditions	Deployment phase	Minimum [m]	Maximum [m]	Range [m]
Low	P1	-1.1	0.9	2
	P2	-0.15	0.3	0.45
Medium	P1	5	7.2	2.2
	P2	-1.5	0.25	1.75
Extreme	P1	10	26	16
	P2	-1.9	2.1	4

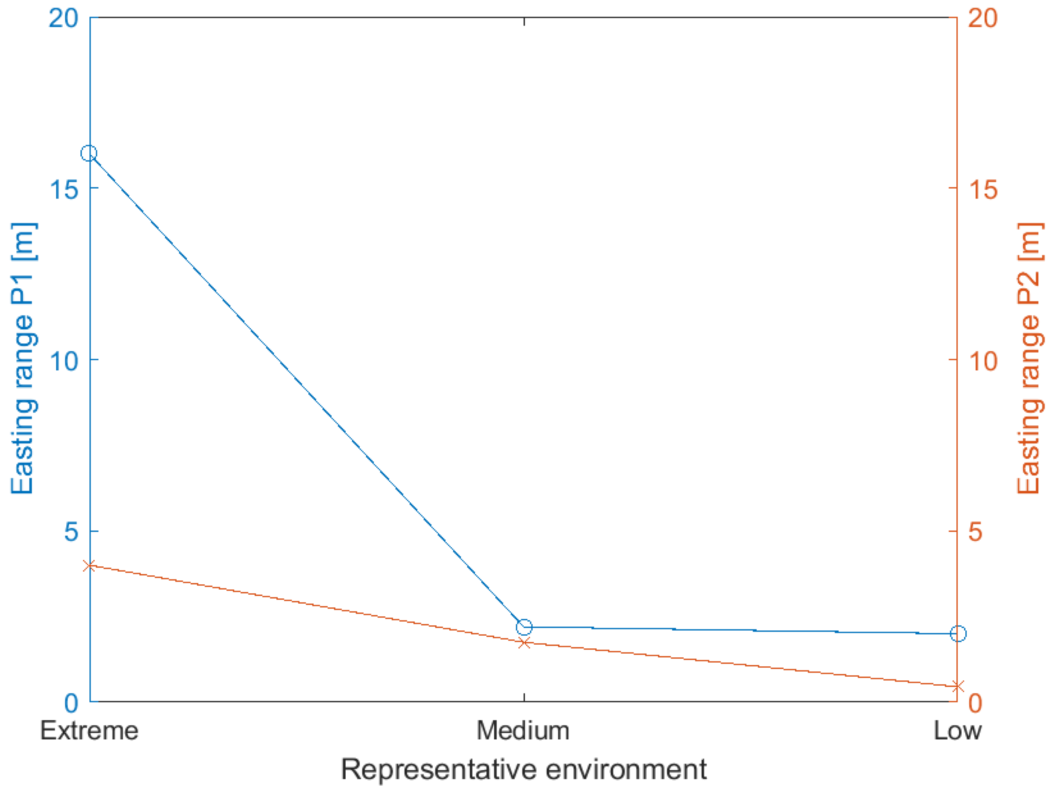


FIGURE. 6-1 COMPARISON OF THE RANGE FOR EASTING IN PHASE 1 AND 2

TABLE. 6-3 EXTREME VALUES AND THE RANGE FOR THE MARMOK NORTHING

Environmental conditions	Deployment phase	Minimum [m]	Maximum [m]	Range [m]
Low	P1	-0.89	0.7	1.59
	P2	-1.1	0.4	1.5
Medium	P1	0.3	2.3	2
	P2	-1.25	1.5	2.75
Extreme	P1	-9	9	18
	P2	-7	4	11

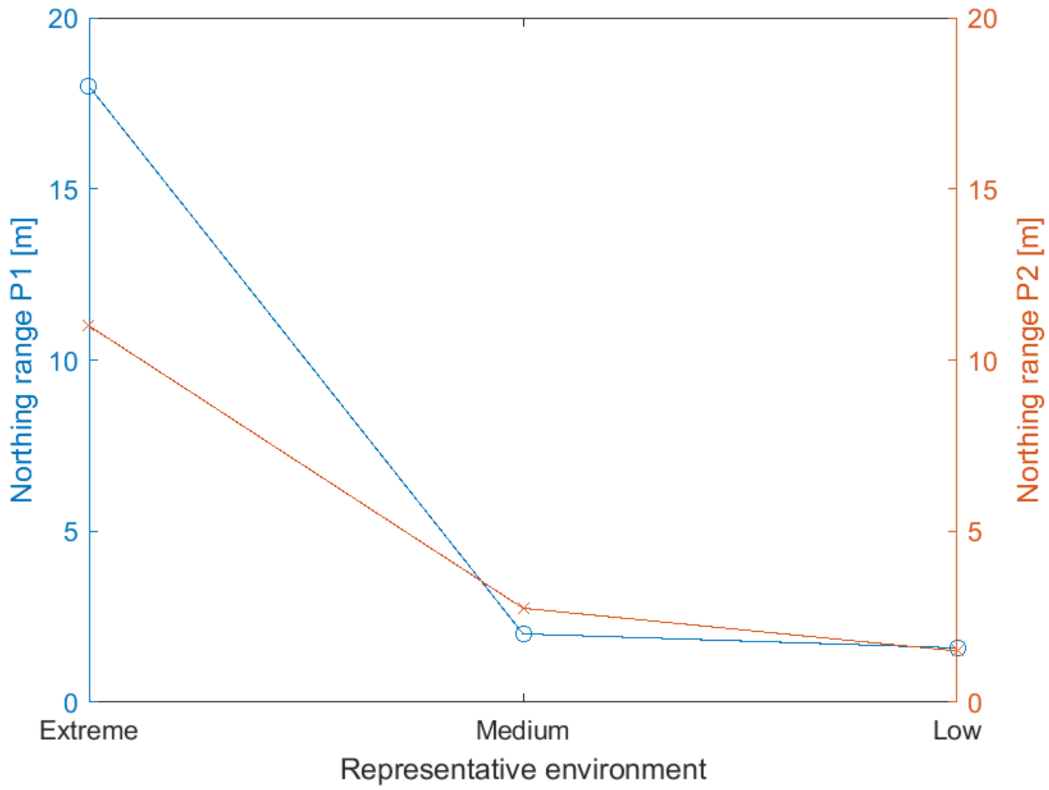


FIGURE. 6-2 COMPARISON OF THE RANGE FOR NORTHING IN PHASE 1 AND 2

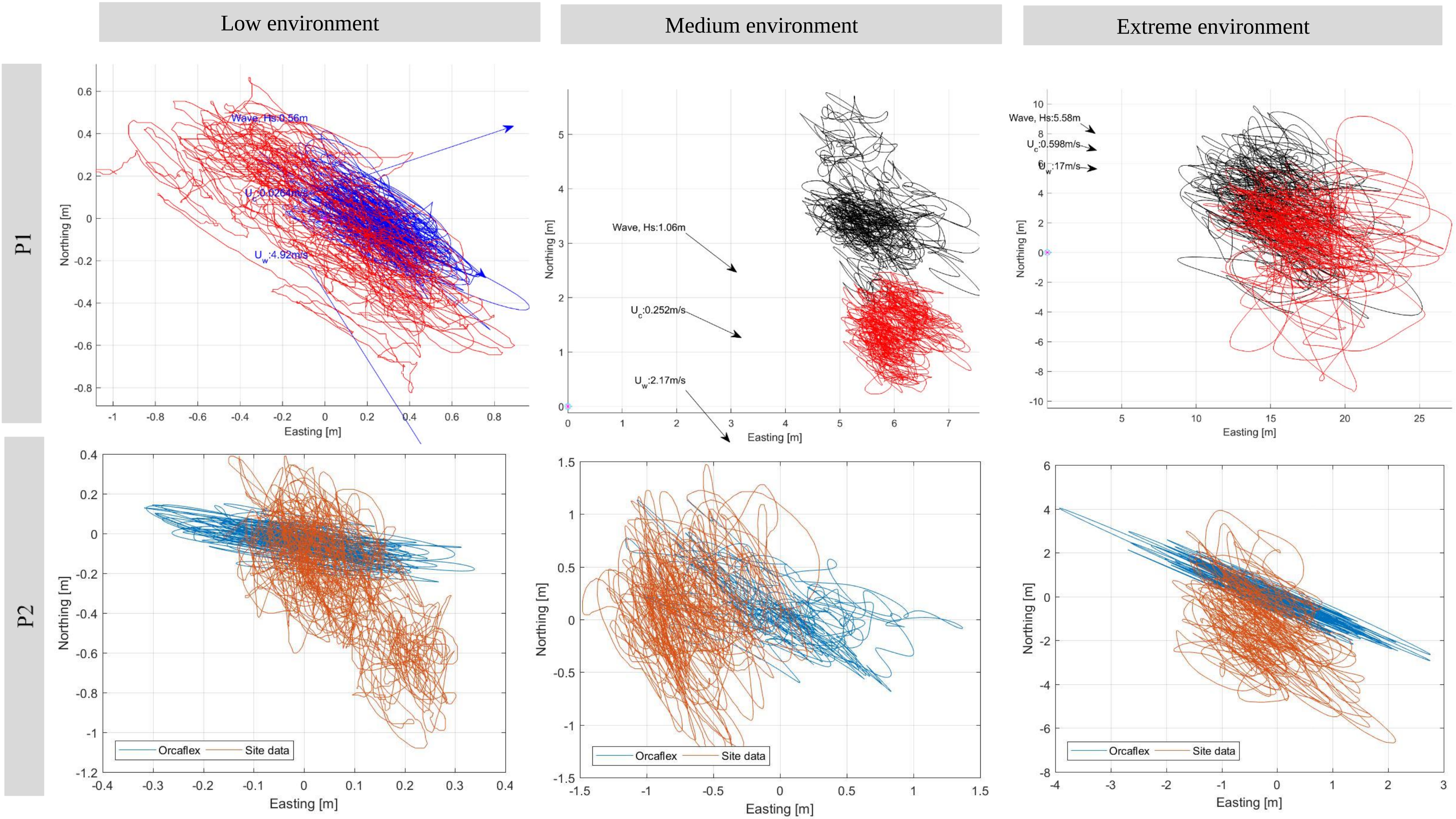


FIGURE. 6-3 COMPARISON BETWEEN EXCURSION PLOTS OF LOW, MEDIUM AND EXTREME ENVIRONMENTS FOR PHASE 1AND PHASE 2 DEPLOYMENTS

6.3 HEAVE

The maxima and minima motion results for Heave were obtained from graphs in Figure 8-14 and 8-15 (section 10). The readings were used to obtain the minimum and maximum range of motion in Heave (Table 6-4) for the three environmental conditions and for both, Phase 1 and Phase 2. The results for Heave are graphically presented in figure 6-4 (minima) and 6-5 (maxima). It can be observed that a motion range is decreasing in Phase 2 for extreme environmental condition. A comparison between Heave spectra for low, medium and extreme environments for Phase 1 and Phase 2 is presented in the graphs in figure 6-6.

TABLE. 6-4 MINIMUM AND MAXIMUM RANGE FOR MARMOK HEAVE IN P1 AND P2

Heave range [m]						
Environmental condition	Low		Medium		Extreme	
	Min	Max	Min	Max	Min	Max
Phase 1	0.18	1.5	0.23	1.95	4.3	16.3
Phase 2	0.08	1.6	0.29	3.5	0.6	6.3

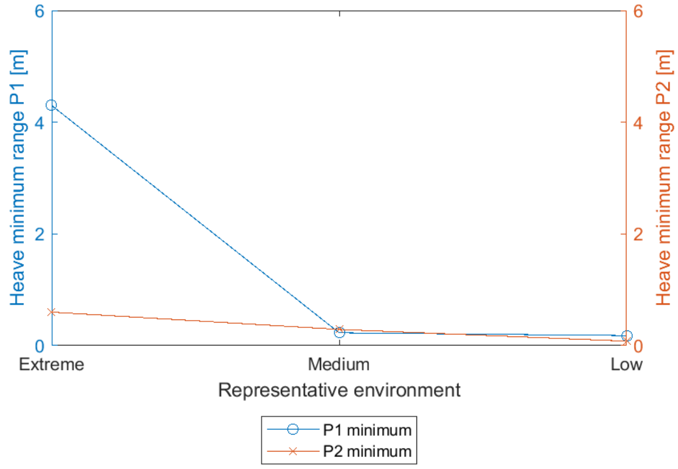


FIGURE. 6-4 COMPARISON OF THE MINIMUM RANGE OF HEAVE FOR P1 AND P2 DEPLOYMENTS

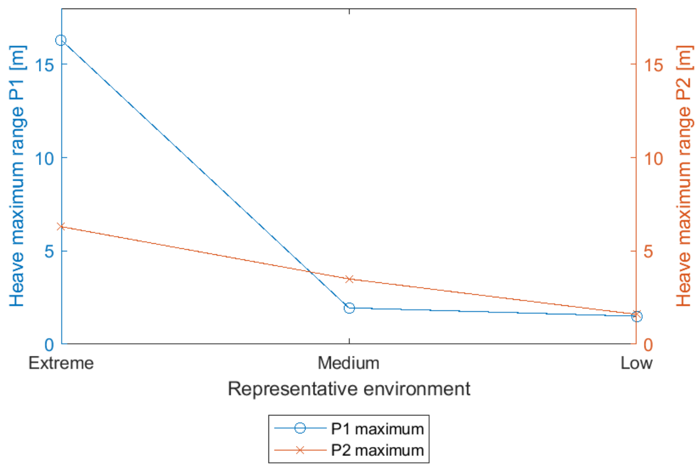


FIGURE. 6-5 COMPARISON OF THE MINIMUM RANGE OF HEAVE FOR P1 AND P2 DEPLOYMENTS

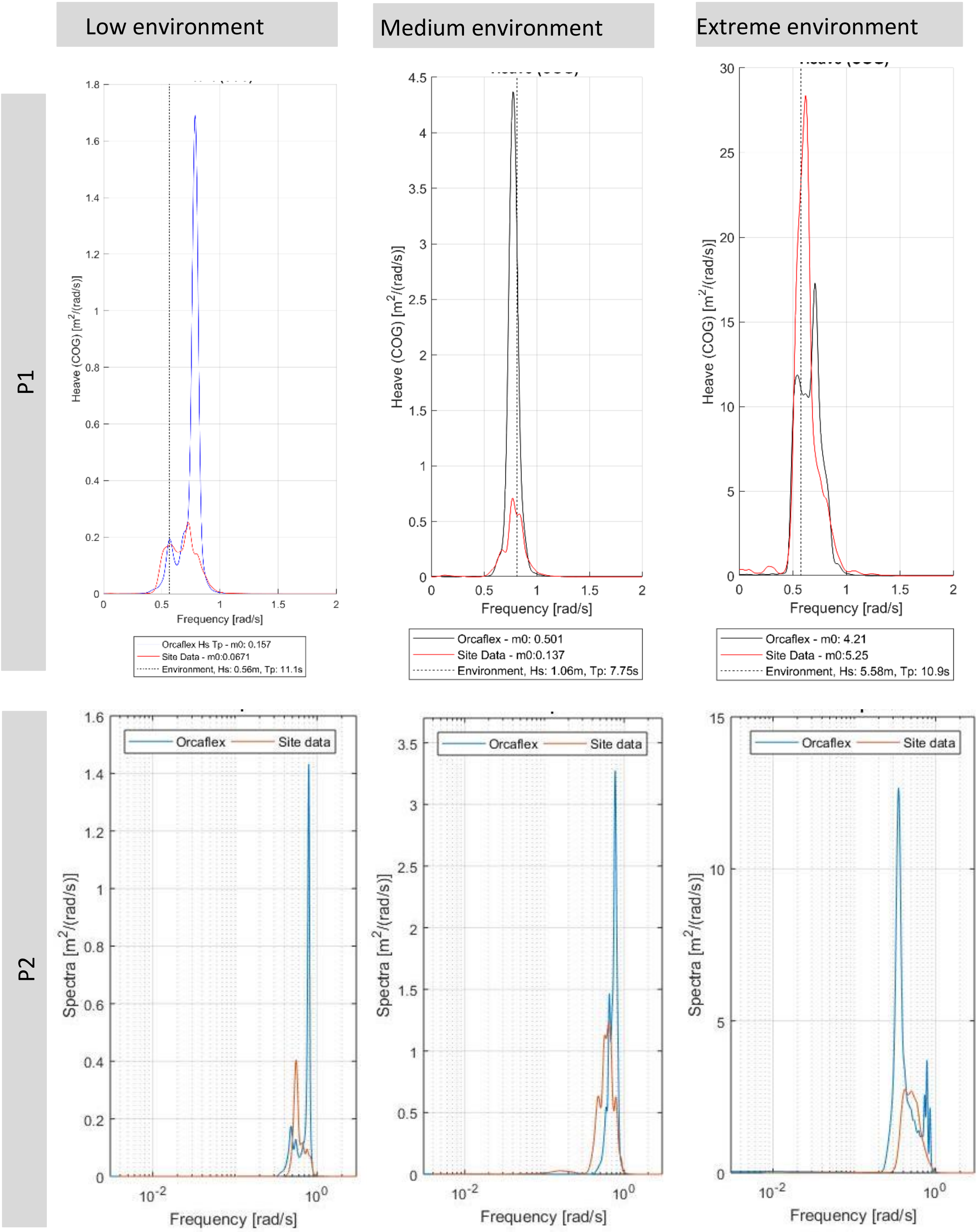


FIGURE. 6-6 COMPARISON BETWEEN HEAVE SPECTRA OF LOW, MEDIUM AND EXTREME ENVIRONMENTS FOR PHASE 1 AND PHASE 2

6.4 ROLL AND PITCH

The maxima and minima rotational motion results in roll and pitch were obtained from time series graphs shown in Figures 8-30 to 8-33 & 8-35, 8-36 (section 12). The readings were used to obtain the minimum and maximum range of roll motion (Table 6-5) and pitch motion (Table 6-6) for the three environmental conditions and for both, Phase 1 and Phase 2. The results for Roll motion are graphically presented for minima and maxima in figure 6-7 and 6-8, respectively; and for Pitch motion in figure 6-9 and 6-10. It can be observed that a motion range is decreasing in Phase 2 for extreme environmental condition. A comparison between Roll and Pitch spectra for low, medium and extreme environments for Phase 1 and Phase 2 are presented in the graphs in figure 6-11 and 6-12, respectively.

TABLE. 6-5 MINIMUM AND MAXIMUM RANGE FOR MARMOK ROLL IN P1 AND P2

Roll range [deg]						
Environmental condition	Low		Medium		Extreme	
	Min	Max	Min	Max	Min	Max
Phase 1	0.24	0.65	0.18	1.7	2.9	41
Phase 2	0.18	0.74	0.55	3.7	1.2	11

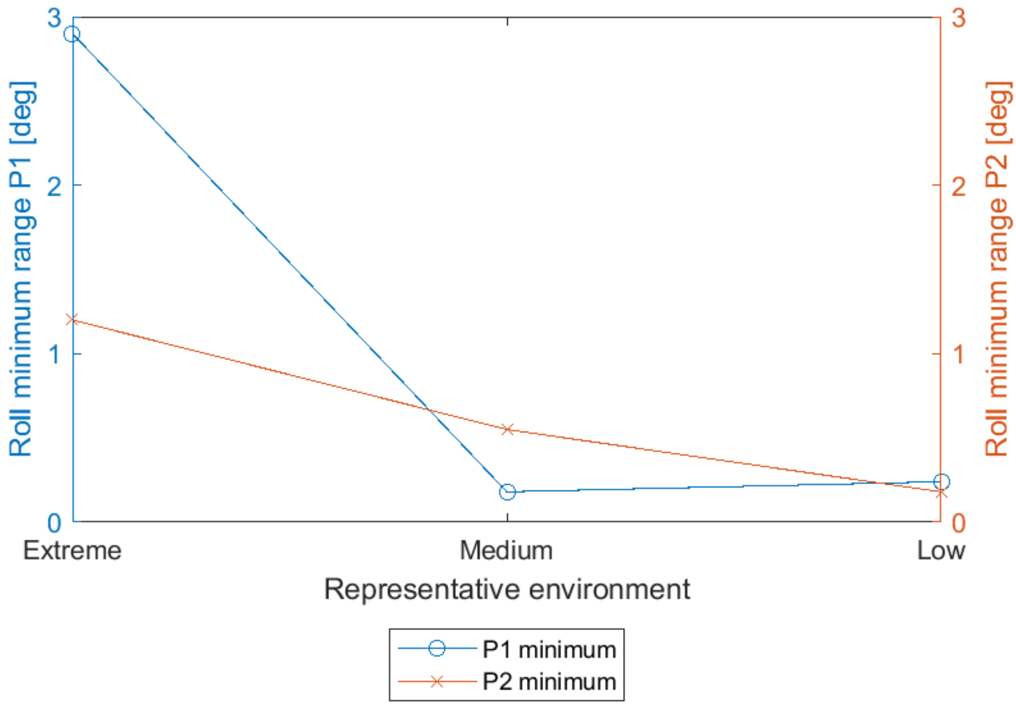


FIGURE. 6-7 COMPARISON OF THE MINIMUM RANGE OF ROLL FOR P1 AND P2 DEPLOYMENTS

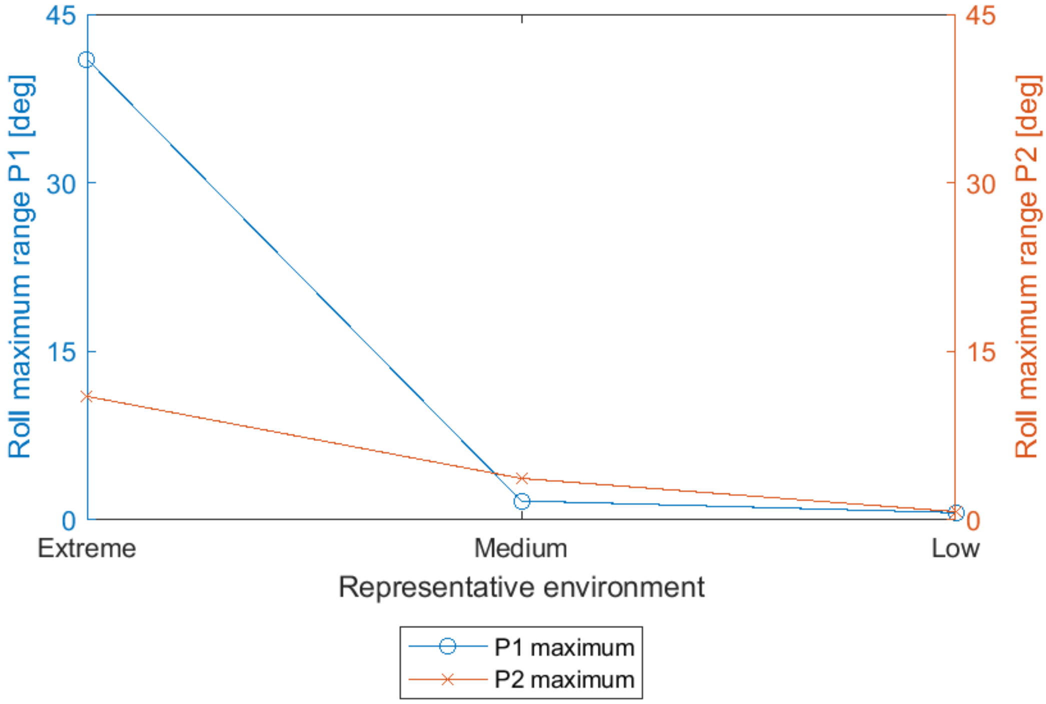


FIGURE. 6-8 COMPARISON OF THE MAXIMUM RANGE OF ROLL FOR P1 AND P2 DEPLOYMENTS

TABLE. 6-6 MINIMUM AND MAXIMUM RANGE FOR MARMOK PITCH IN P1 AND P2

Pitch range [deg]						
Environmental condition	Low		Medium		Extreme	
	Min	Max	Min	Max	Min	Max
Phase 1	0.18	1.35	0.4	2.8	1.9	24
Phase 2	0.21	1.22	0.9	5.3	1.3	16

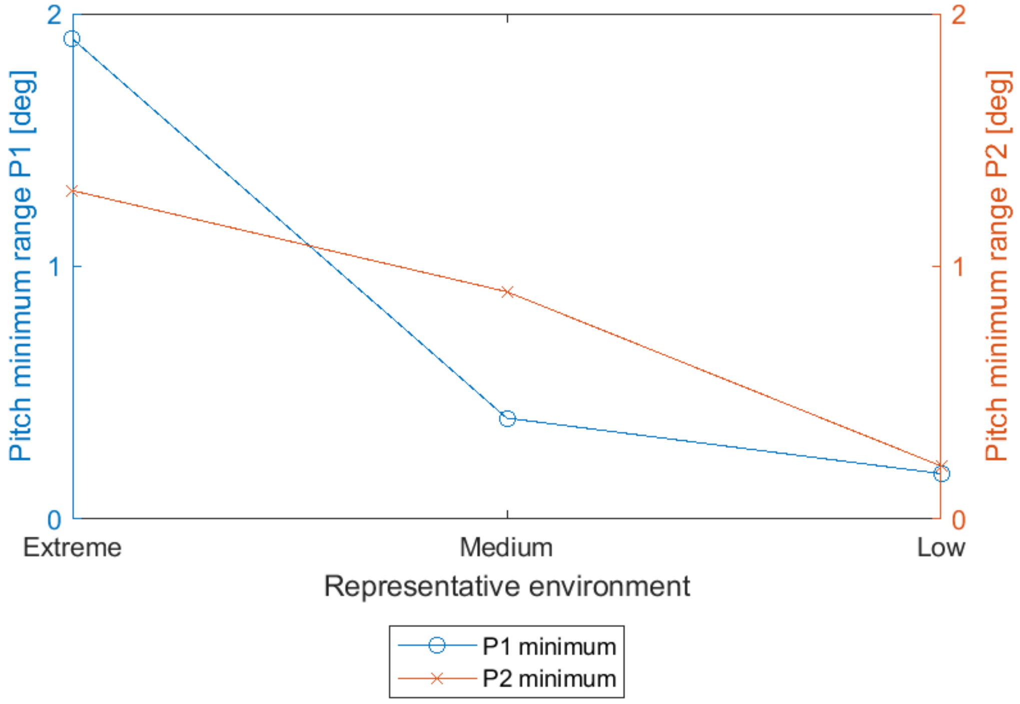


FIGURE. 6-9 COMPARISON OF THE MINIMUM RANGE OF PITCH FOR P1 AND P2 DEPLOYMENTS

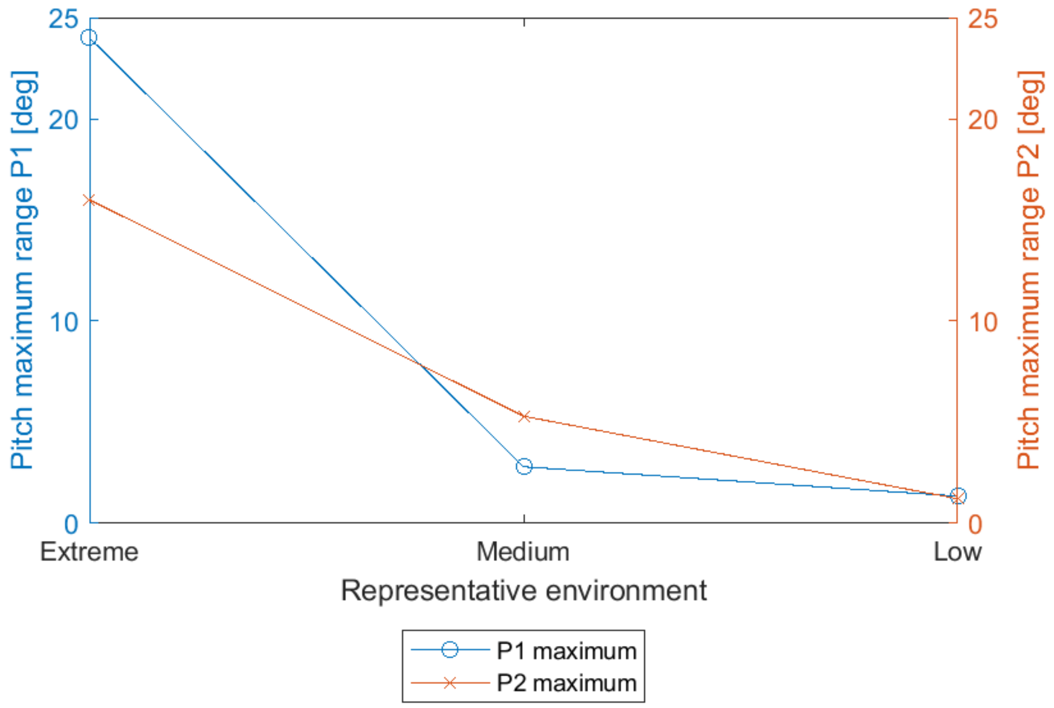


FIGURE. 6-10 COMPARISON OF THE MAXIMUM RANGE OF PITCH FOR P1 AND P2 DEPLOYMENT

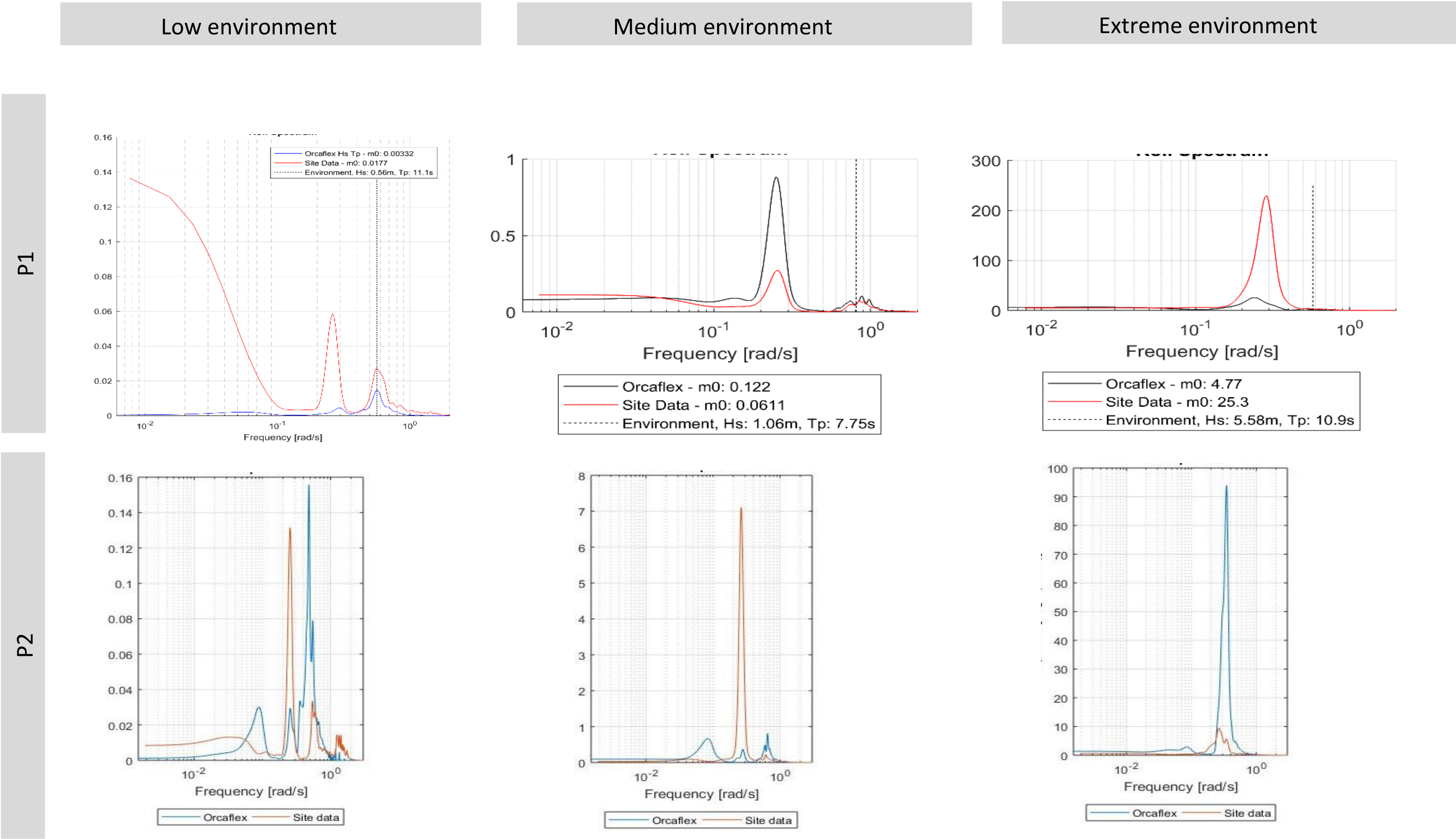


FIGURE. 6-11 COMPARISON BETWEEN ROLL SPECTRA OF LOW, MEDIUM AND EXTREME ENVIRONMENTS FOR PHASE 1AND PHASE 2 DEPLOYMENTS

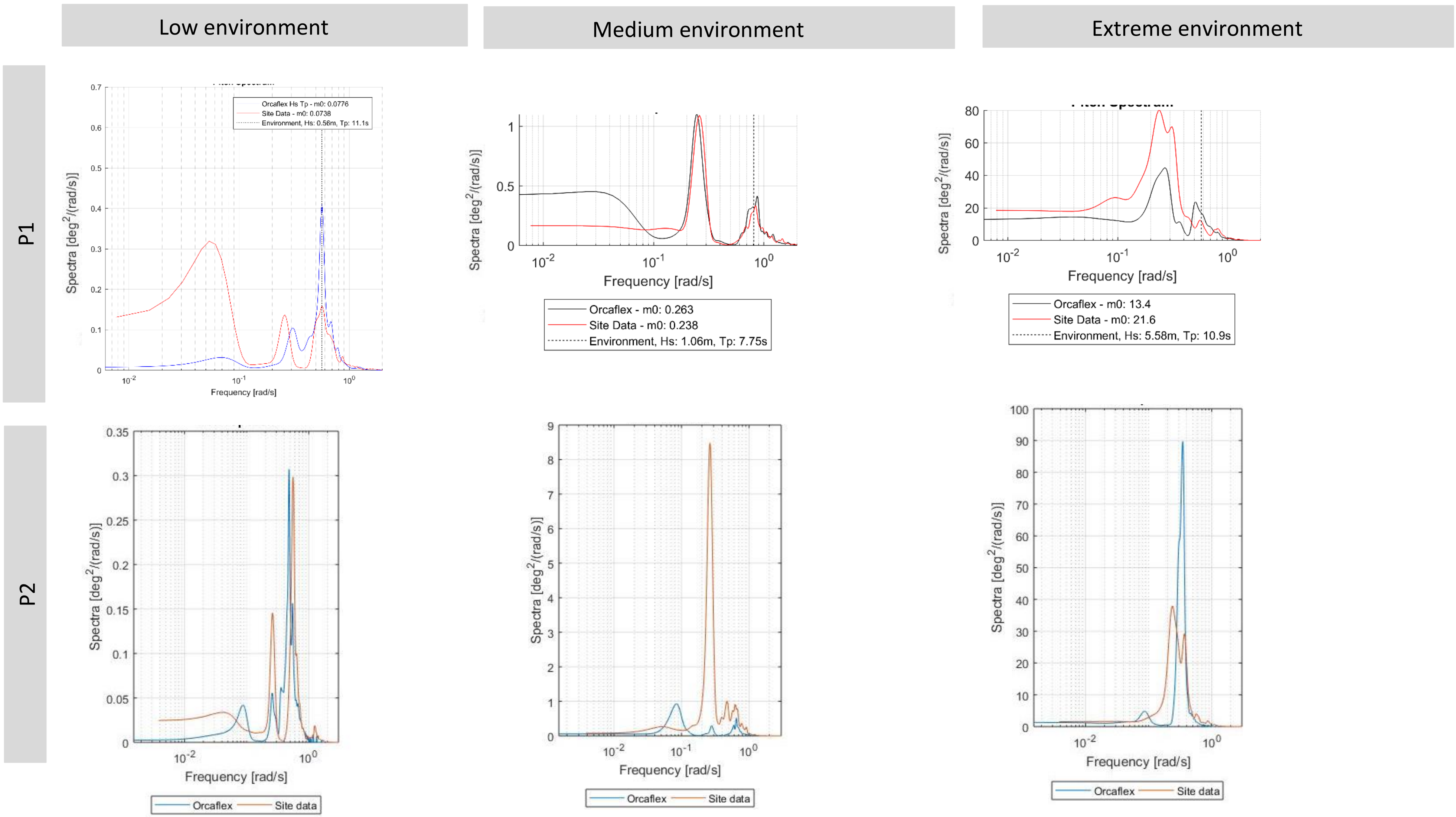


FIGURE. 6-12 COMPARISON BETWEEN PITCH SPECTRA OF LOW, MEDIUM AND EXTREME ENVIRONMENTS FOR PHASE 1AND PHASE 2 DEPLOYMENTS

6.5 TENSION

The tension results were analysed from time series graphs shown in Figures 8-43 to 8-46 & 8-49, 8-50 (section 14). The readings were used to obtain the maxima range of tension motion (Table 6-7) and maximum and averaged maxima values (Table 6-8) for the three environmental conditions and for both, Phase 1 and Phase 2. The results for tension range and averaged maxima values (obtained from 5 readings) are graphically presented in figure 6-15 and 6-16, respectively. It can be observed that the tension range is decreasing by approximate 50% in Phase 2 for extreme environmental condition. The mean and st. dev results are graphically presented for low, medium and extreme environments for Phase 1 and Phase 2 in figure 6-13 and 6-14, respectively.

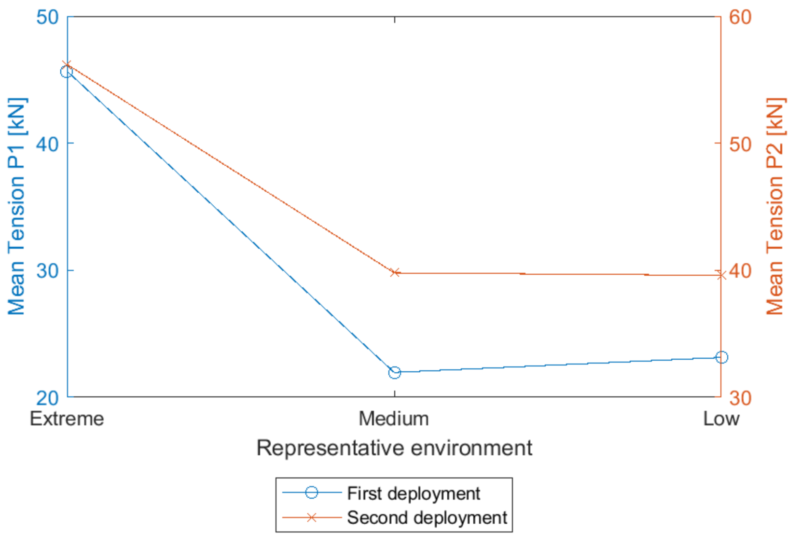


FIGURE. 6-13 COMPARISON OF MEAN TENSION FOR PHASE 1 AND 2 DEPLOYMENTS

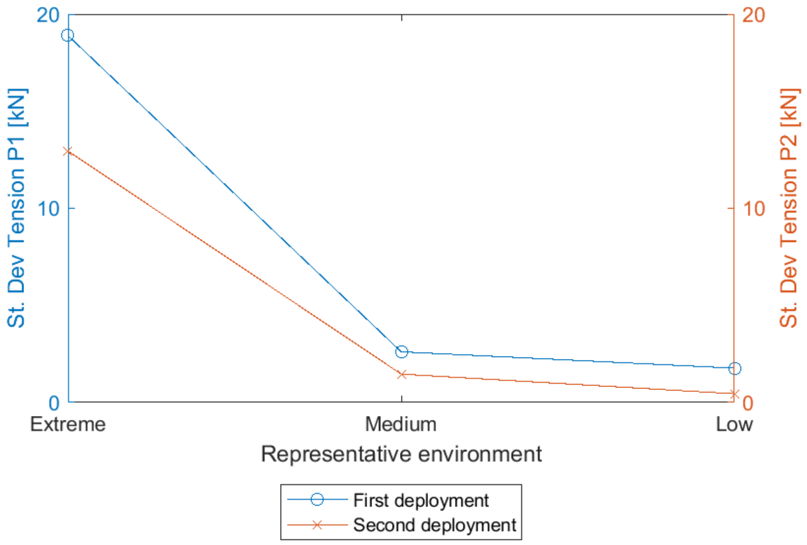


FIGURE. 6-14 COMPARISON OF STANDARD DEVIATION OF TENSION FOR PHASE 1 AND 2 DEPLOYMENTS

TABLE. 6-7 MAXIMUM VALUES AND AVERAGE MAXIMA FOR MARMOK TENSION IN P1 AND P2

Tension range [kN]			
Environmental condition	Low	Medium	Extreme
Phase 1	21	20.5	162
Phase 2	3.9	10.3	83

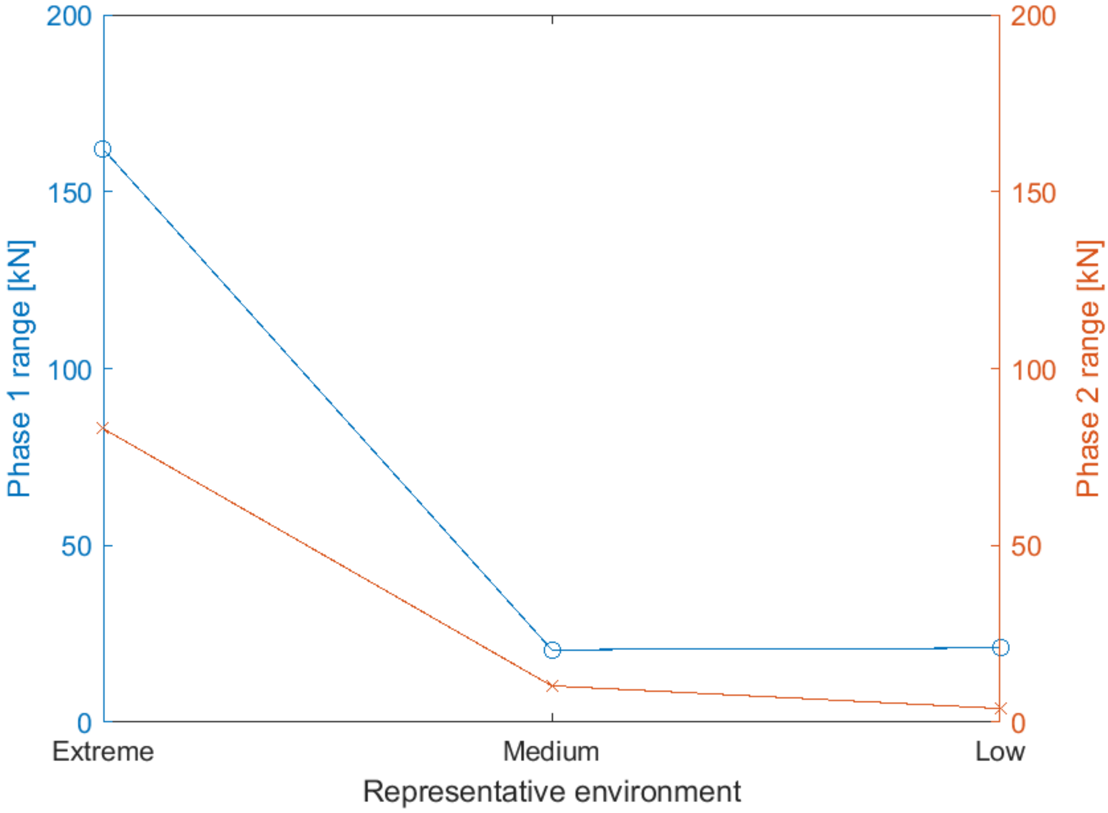


FIGURE. 6-15 COMPARISON OF THE RANGE OF TENSION FOR P1 AND P2 DEPLOYMENTS

TABLE. 6-8 MAXIMUM VALUES AND AVERAGE MAXIMA FOR MARMOK TENSION IN P1 AND P2

Environmental conditions	Deployment phase	Maxima					Average Maxima
Low	P1	33	33	33.5	34	33.5	33.4
	P2	41.5	41.3	41.3	41.2	41.2	41.3
Medium	P1	35	33	32.5	32.5	32	33
	P2	52.5	49	49	47.5	47.5	49.1
Extreme	P1	225	180	175	165	150	179
	P2	130	117	98	97	97	107.8

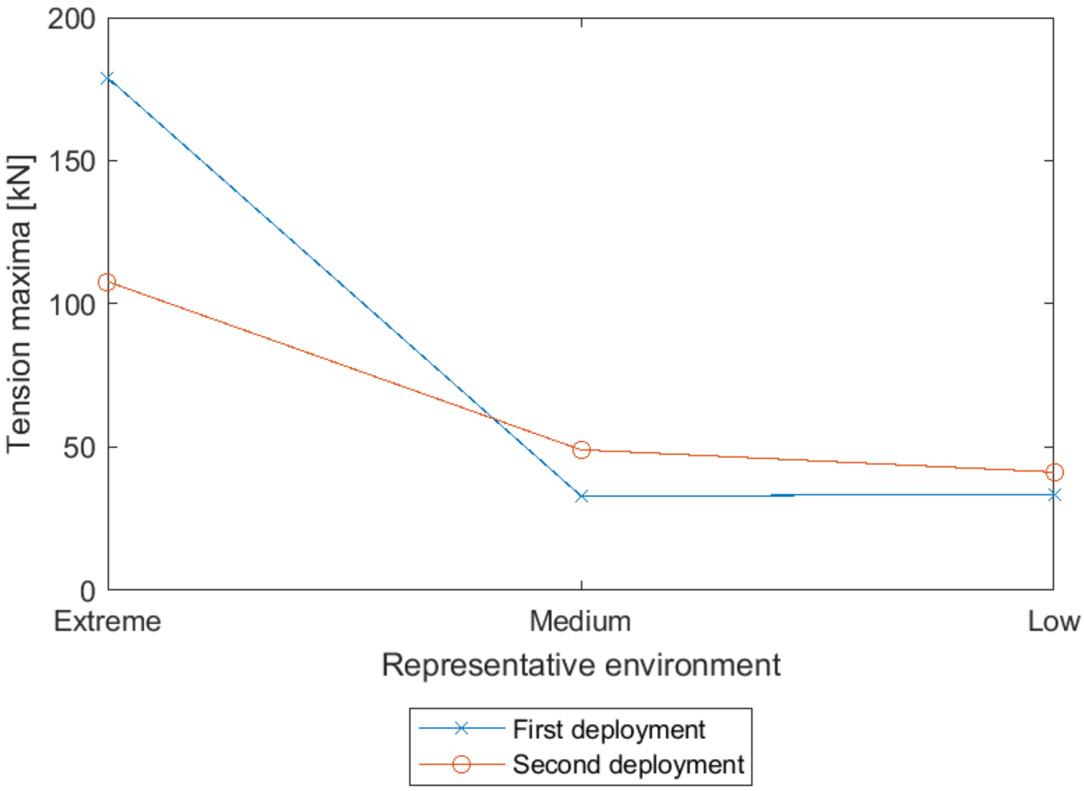


FIGURE. 6-16 AVERAGE MAXIMA FOR MARMOK TENSION IN DEPLOYMENT PHASE 1 AND 2

7. REFERENCES

[1] WP2_GM_102_v1, “Convergence and Robustness Tests”, 2016-04-04

[2] WP2_GM_101_v2, “Review of Oceantec-Idom's Orcaflex Model”, Version 2, 2016-07-05

[3] WP2_GM_103_v1, “Basic Responses”, Version 1.0, 2016-07-05

8. ANNEX I: ORCAFLEX ENVIRONMENT DIRECTIONS

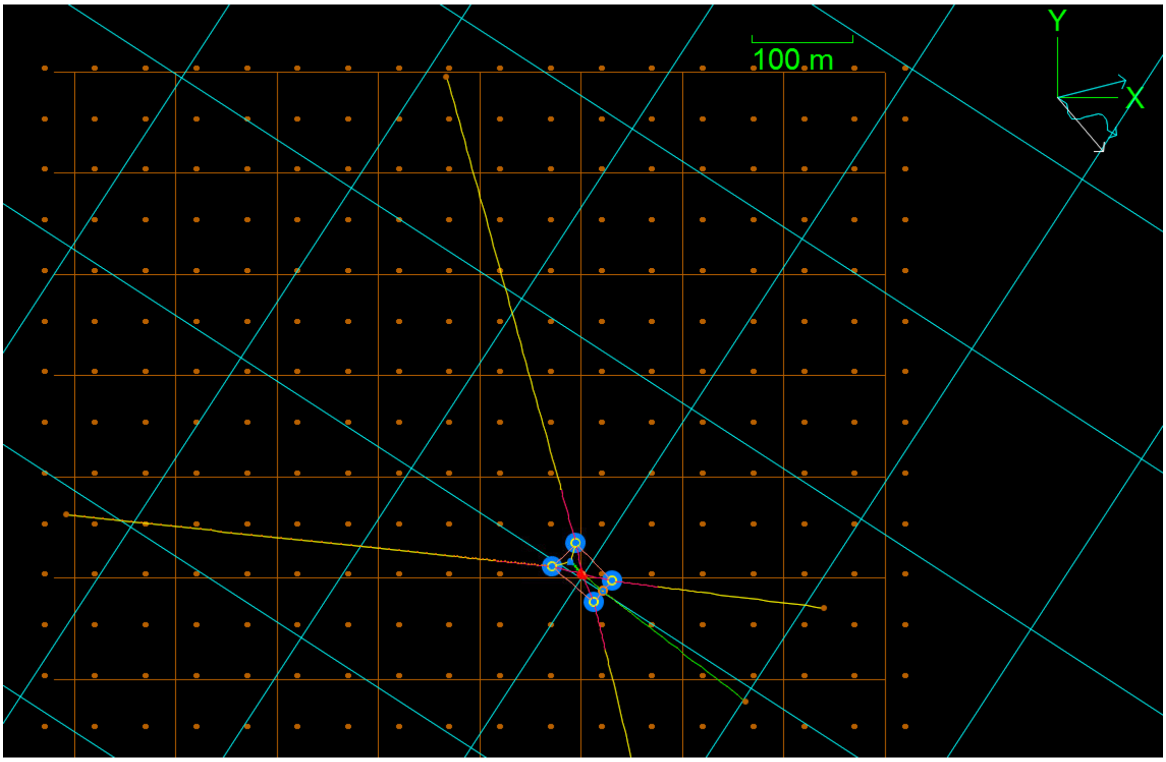


FIGURE. 8-1 ENVIRONMENT DIRECTION IN ORCAFLEX FOR LOW ENVIRONMENT – ENV000P1

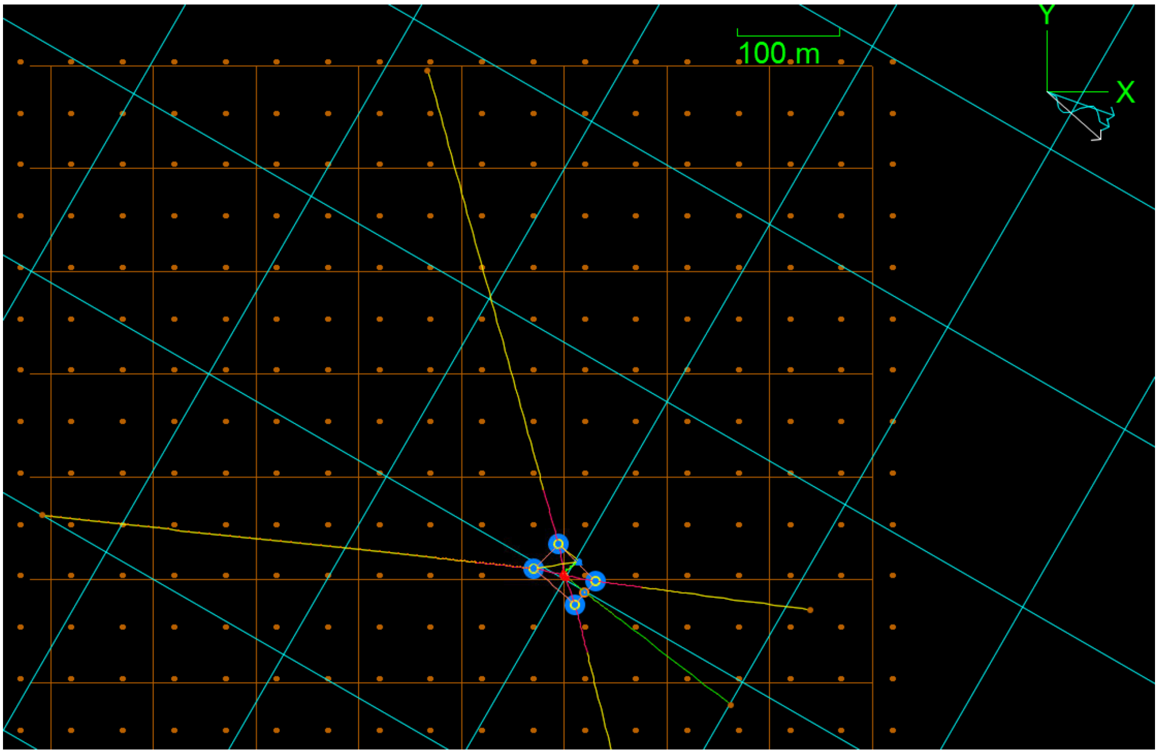


FIGURE. 8-2 ENVIRONMENT DIRECTION IN ORCAFLEX FOR ENV101P1

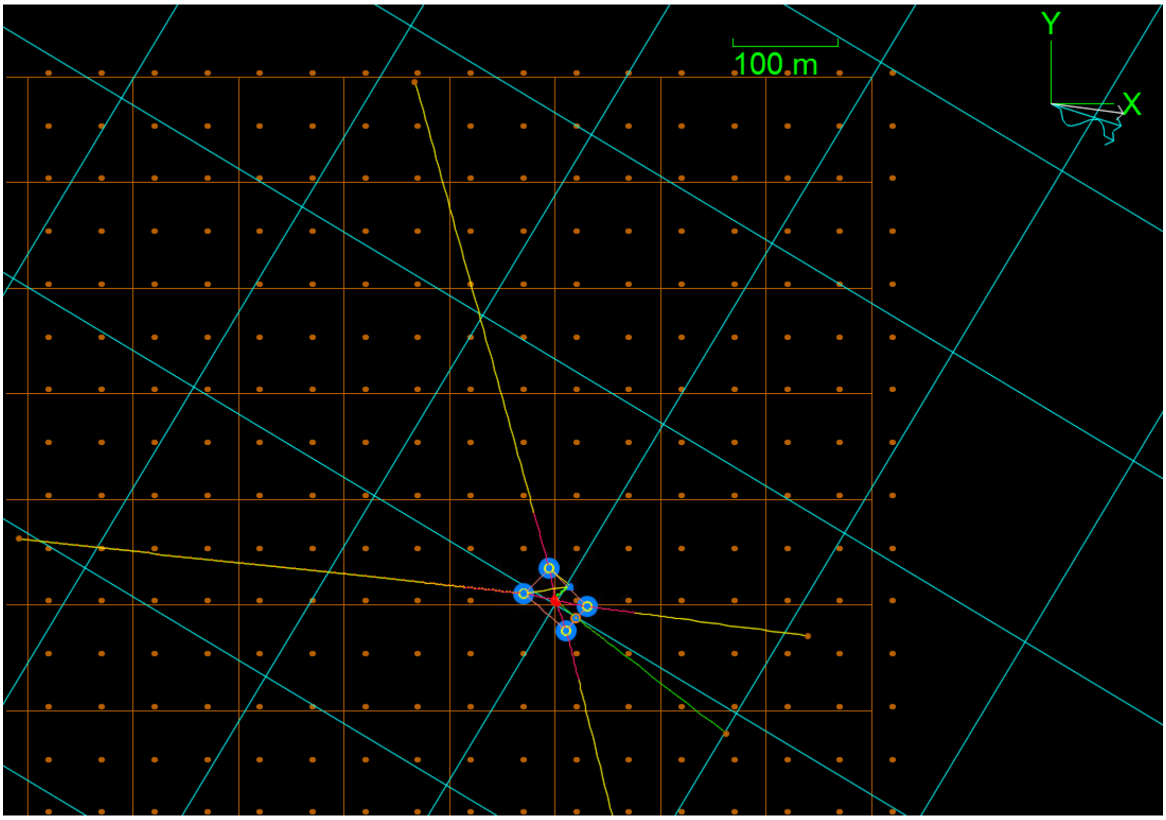


FIGURE. 8-3 ENVIRONMENT DIRECTION IN ORCAFLEX FOR ENV102P1

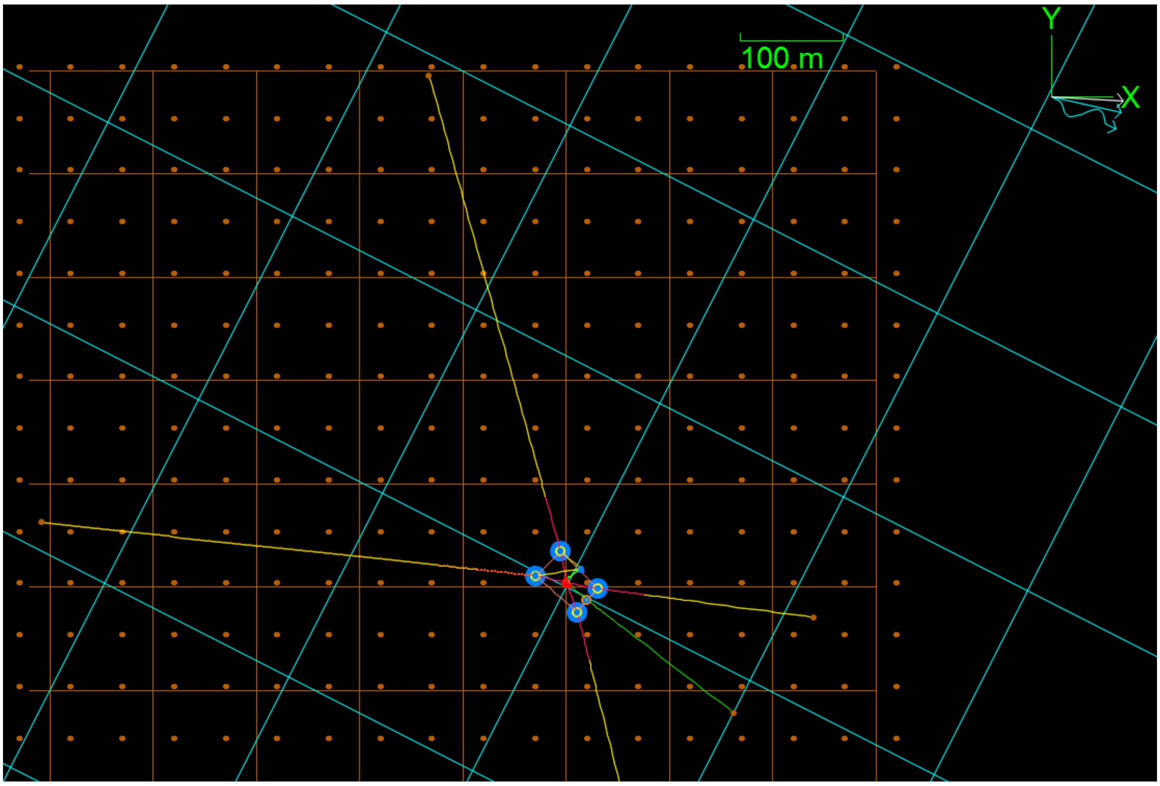


FIGURE. 8-4 ENVIRONMENT DIRECTION IN ORCAFLEX FOR ENV103P1

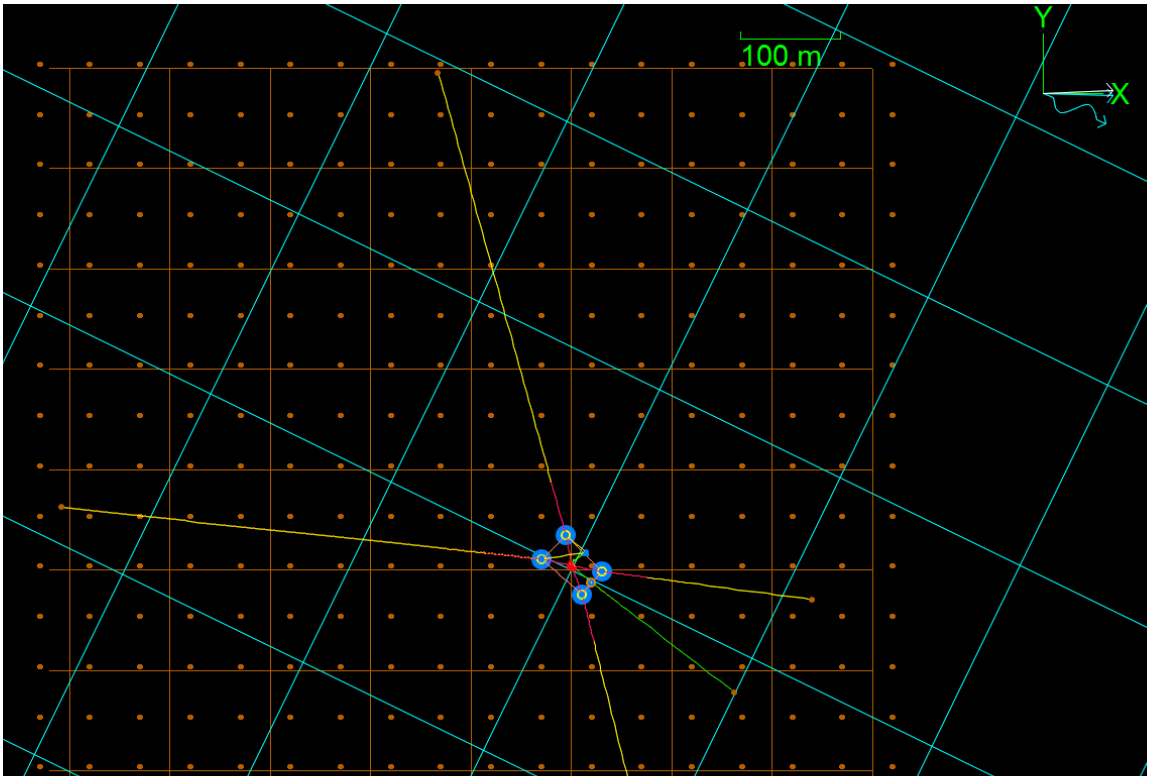


FIGURE. 8-5 ENVIRONMENT DIRECTION IN ORCAFLEX FOR ENV104P

9. ANNEX II: EXCURSION PLOTS OF DGPS ANTENNA

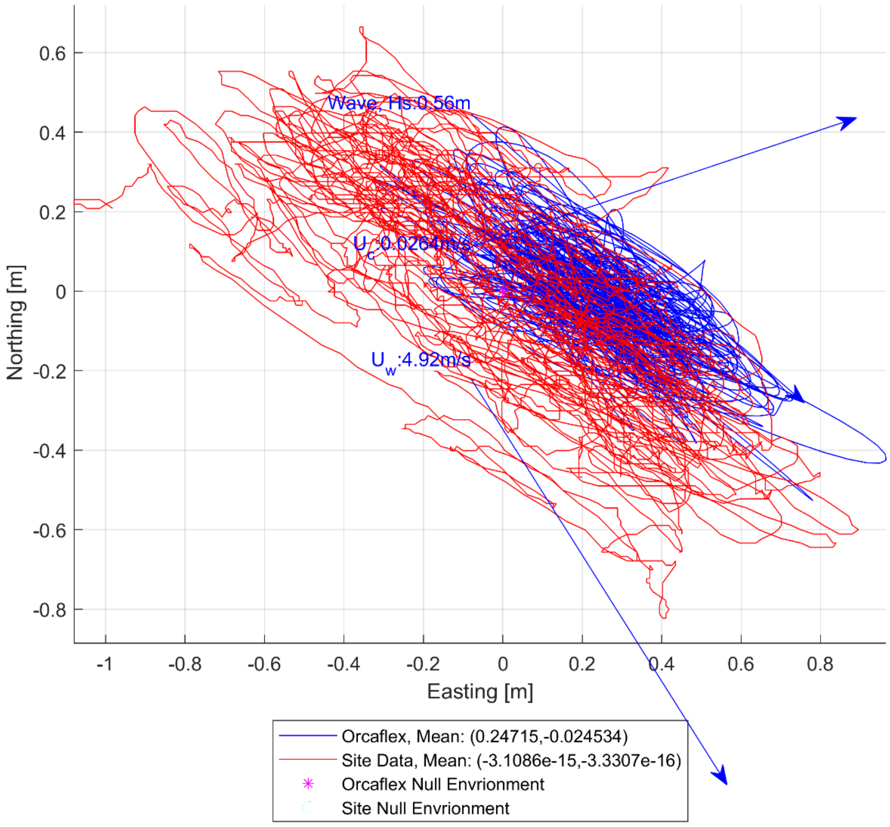


FIGURE. 9-1 EXCURSION PLOT – LOW ENVIRONMENT – ENV000P1

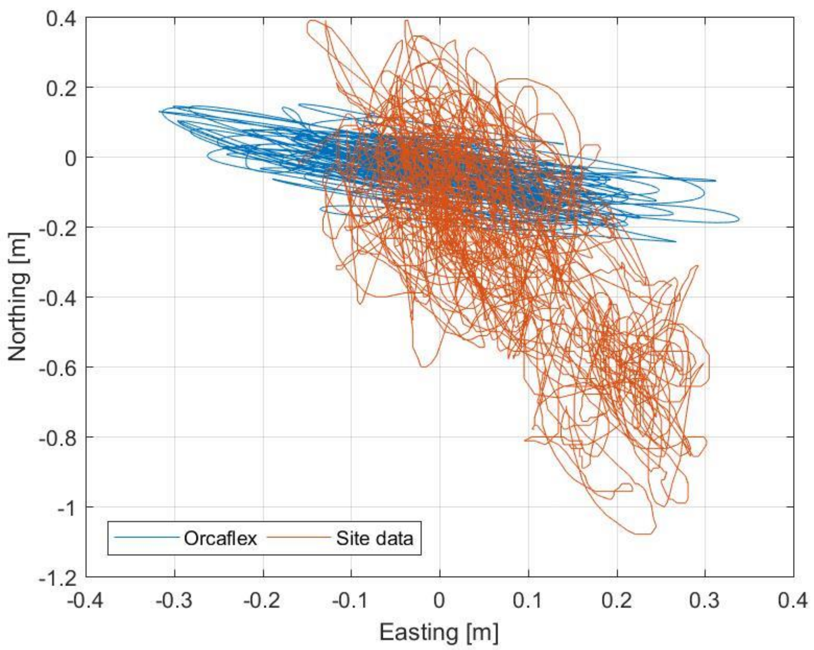


FIGURE. 9-2 EXCURSION PLOT – LOW ENVIRONMENT – ENV000P2

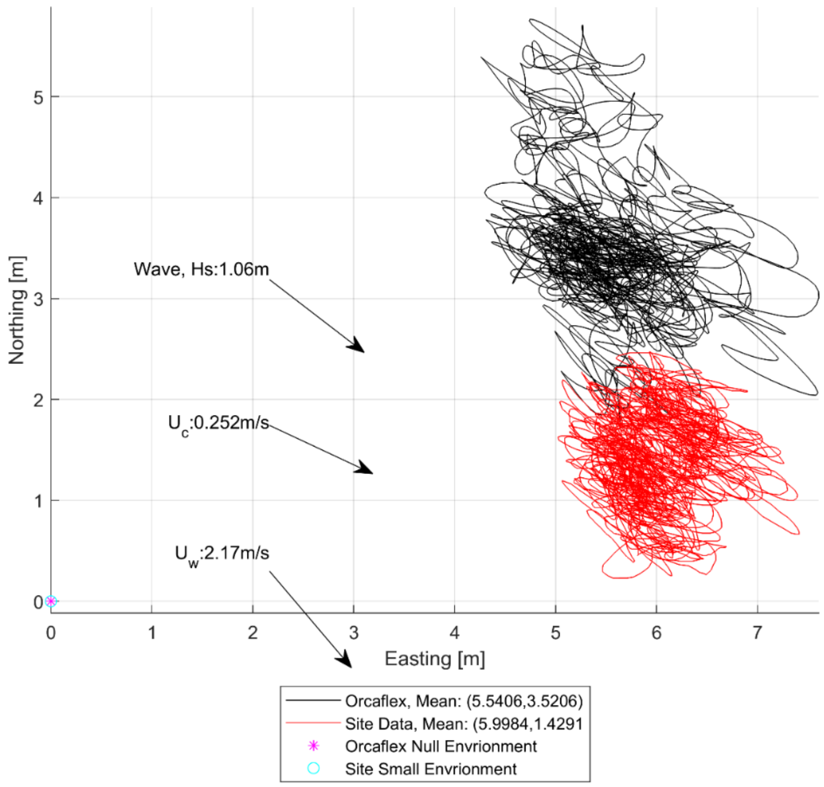


FIGURE. 9-3 EXCURSION PLOT – MEDIUM ENVIRONMENT - ENV 101P1

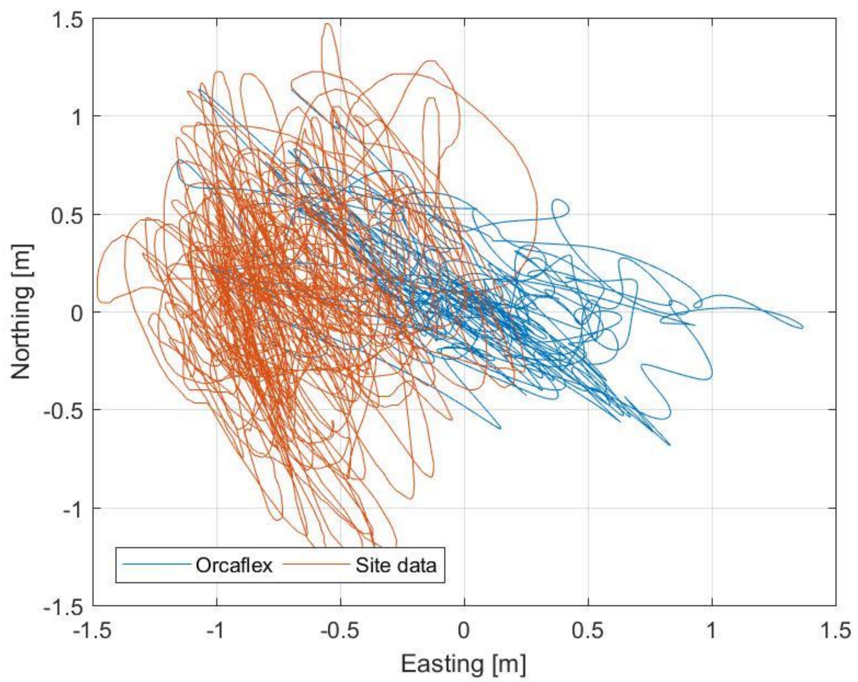


FIGURE. 9-4 EXCURSION PLOT – MEDIUM ENVIRONMENT - ENV 101P2

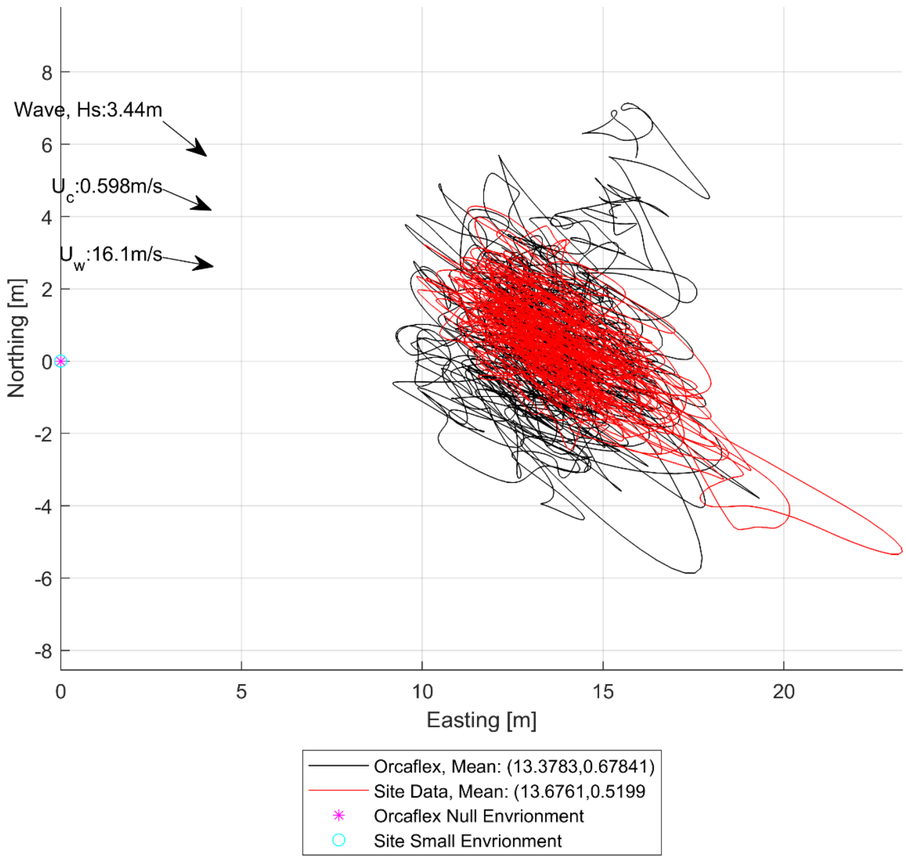


FIGURE. 9-5 EXCURSION PLOT – ENV102P1

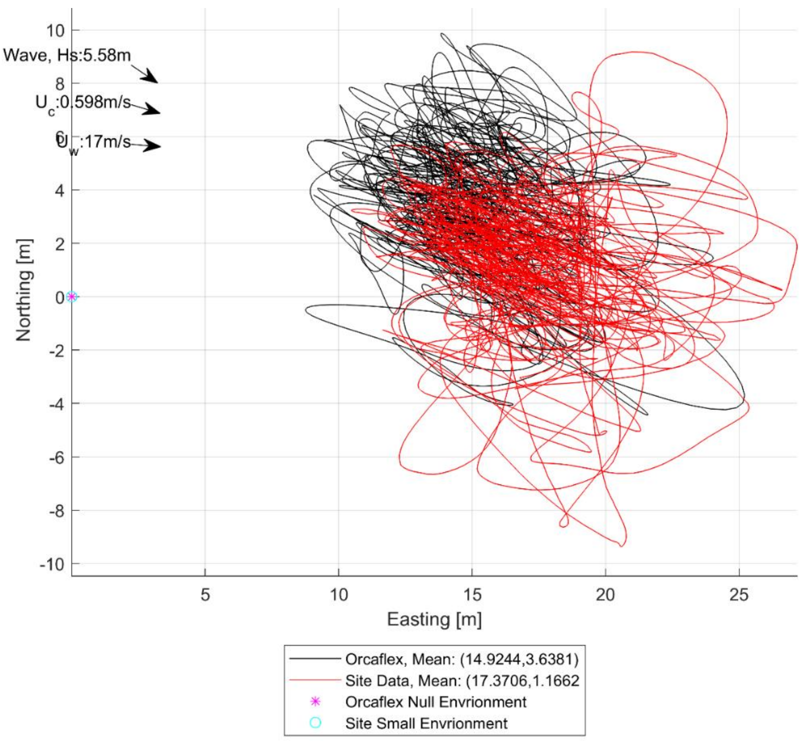


FIGURE. 9-6 EXCURSION PLOT – EXTREME ENVIRONMENT - ENV103P1

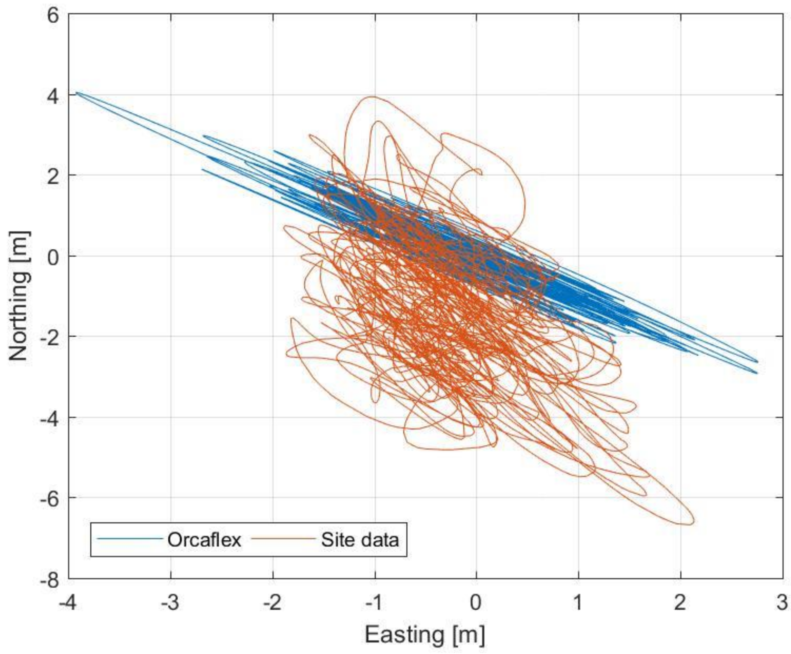


FIGURE. 9-7EXCURSION PLOT - EXTREME ENVIRONMENT - ENV103P2

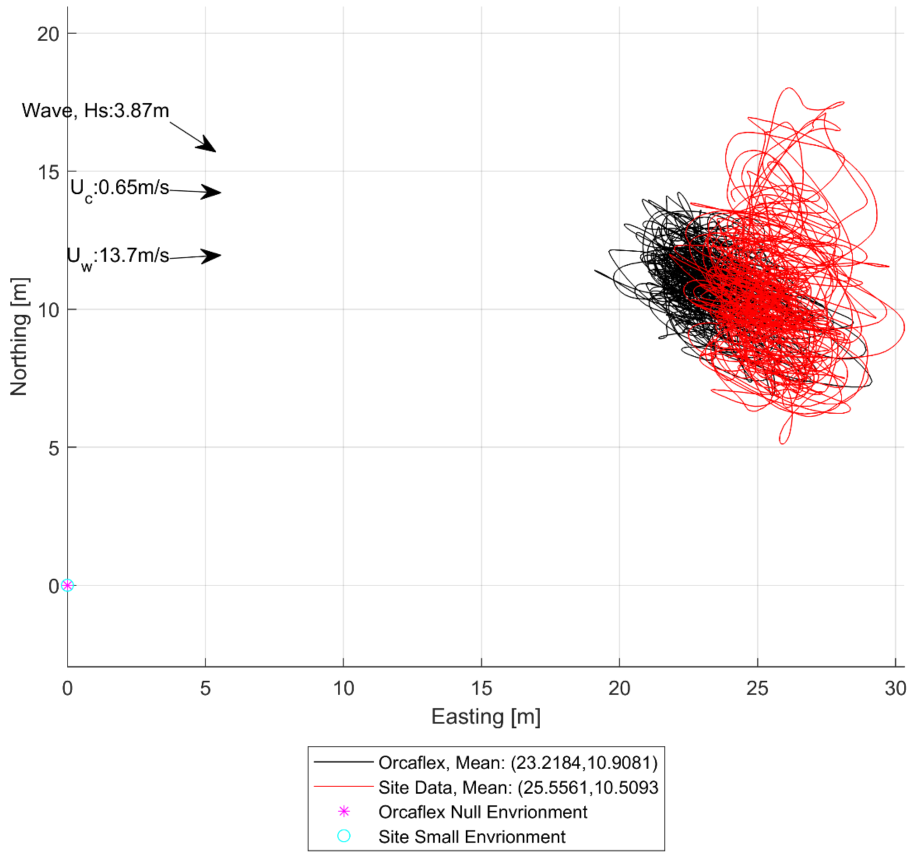
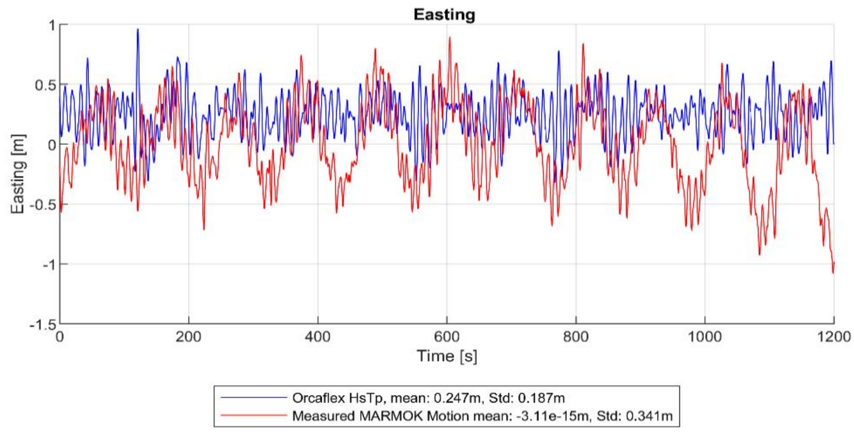
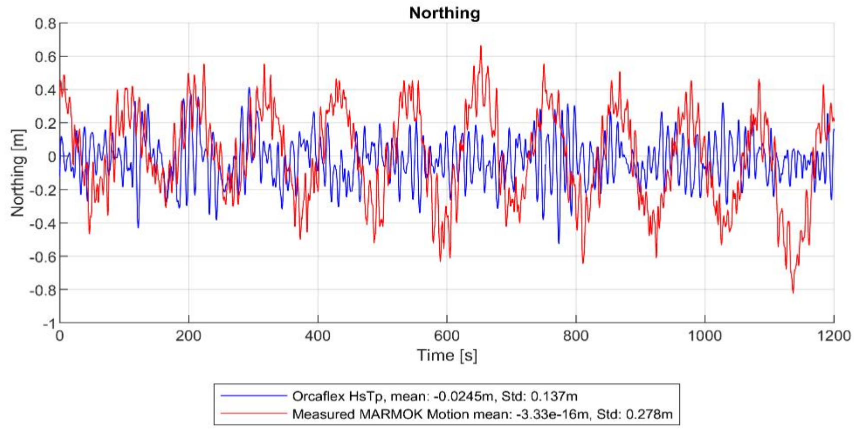


FIGURE. 9-8 EXCURSION PLOT – ENV 104P1

10. ANNEX III: TIME TRACE OF EASTING & NORTHING OF DGPS ANTENNA & HEAVE TIMES SERIES OF COG





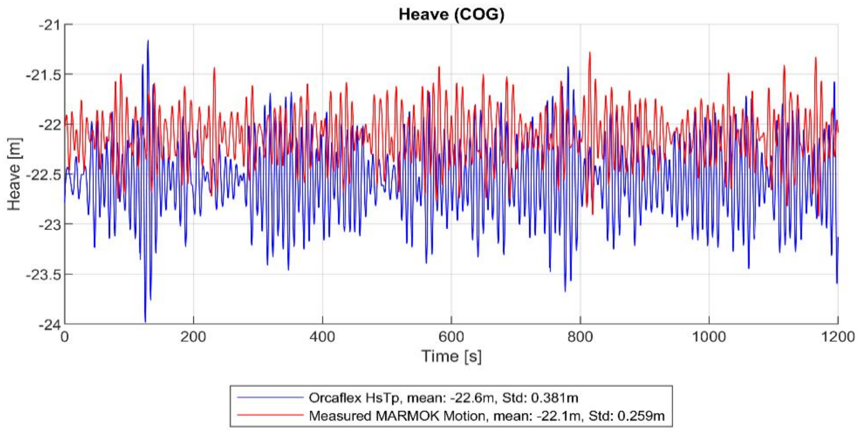


FIGURE. 10-1 TIME TRACE – LOW ENVIRONMENT – ENV000P1

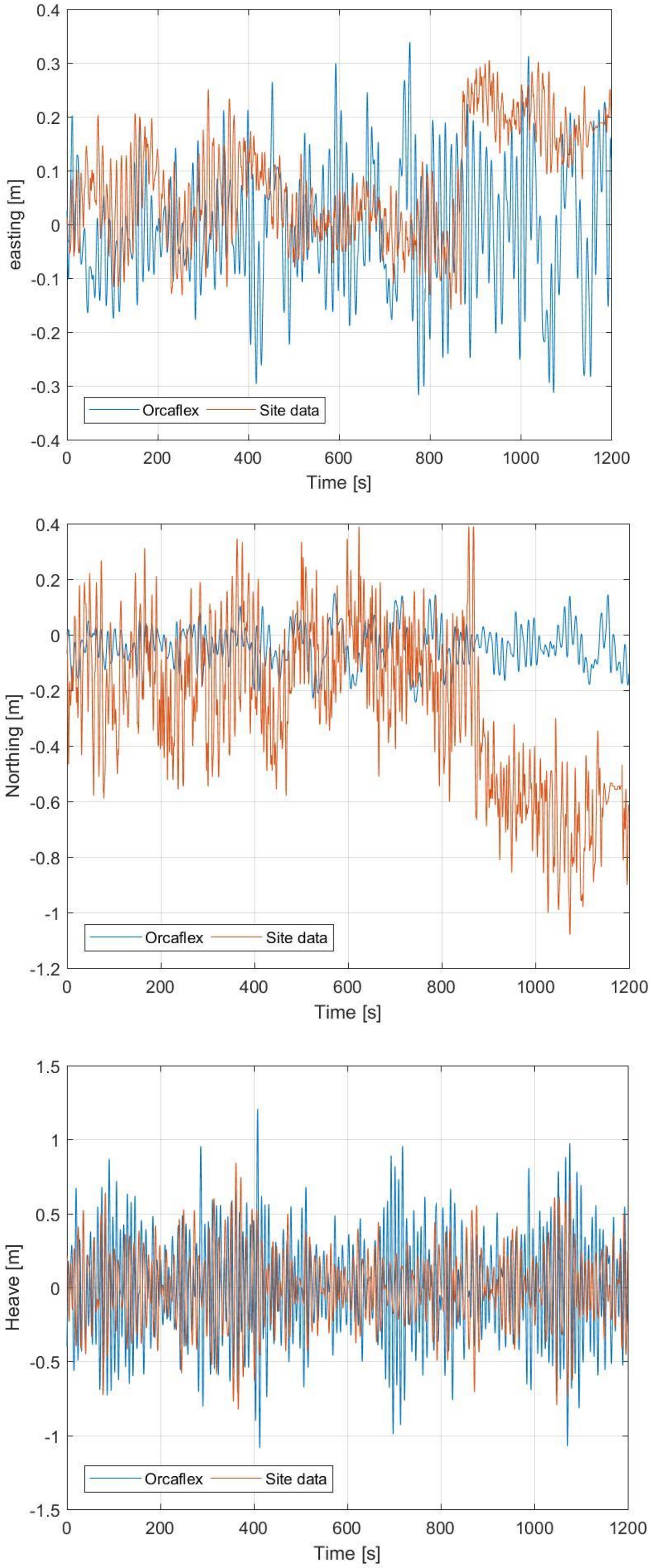


FIGURE. 10-2 TIME TRACE – LOW ENVIRONMENT – ENV000P2

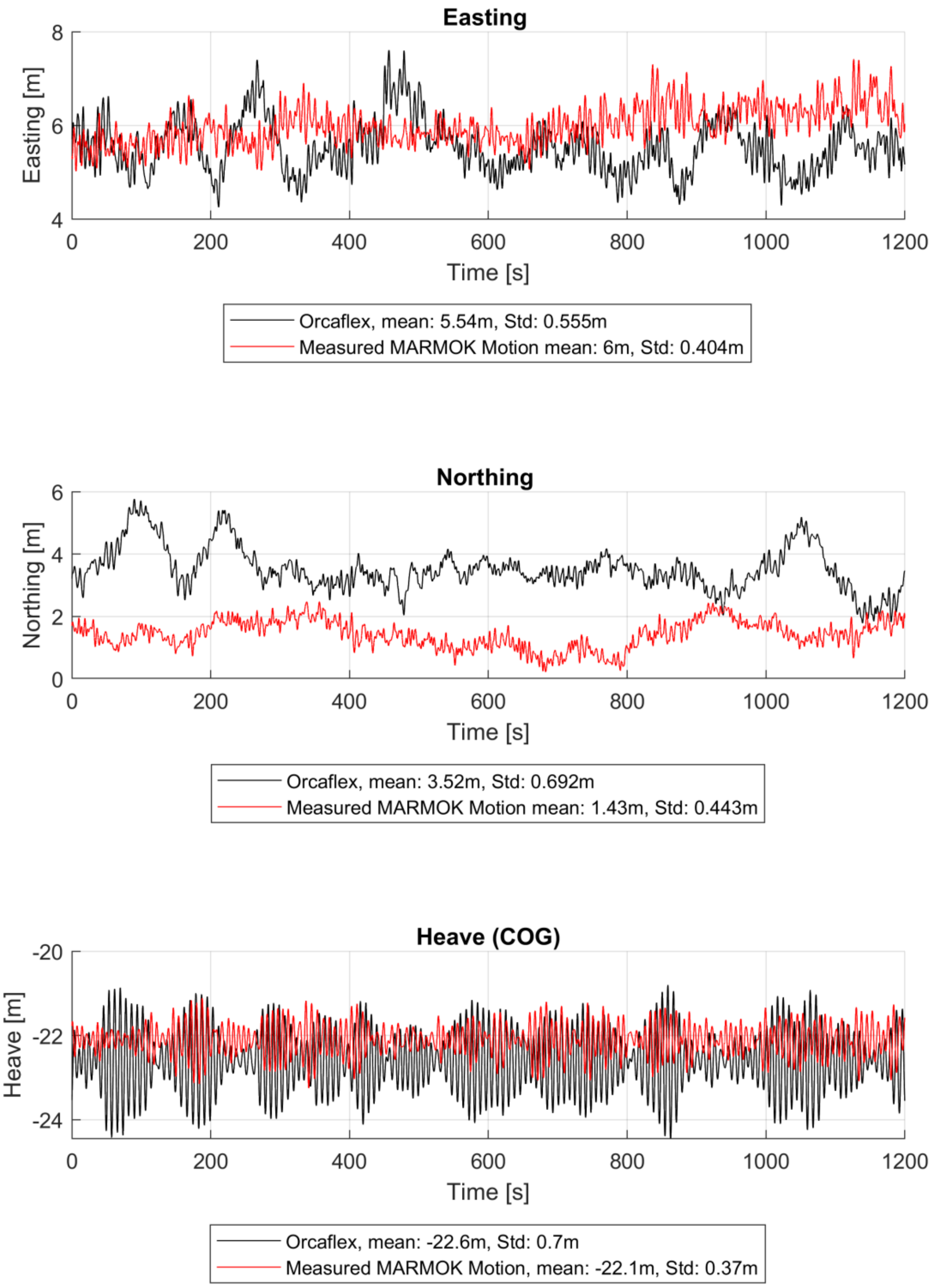


FIGURE. 10-3 TIME TRACE – MEDIUM ENVIRONMENT - ENV101P1

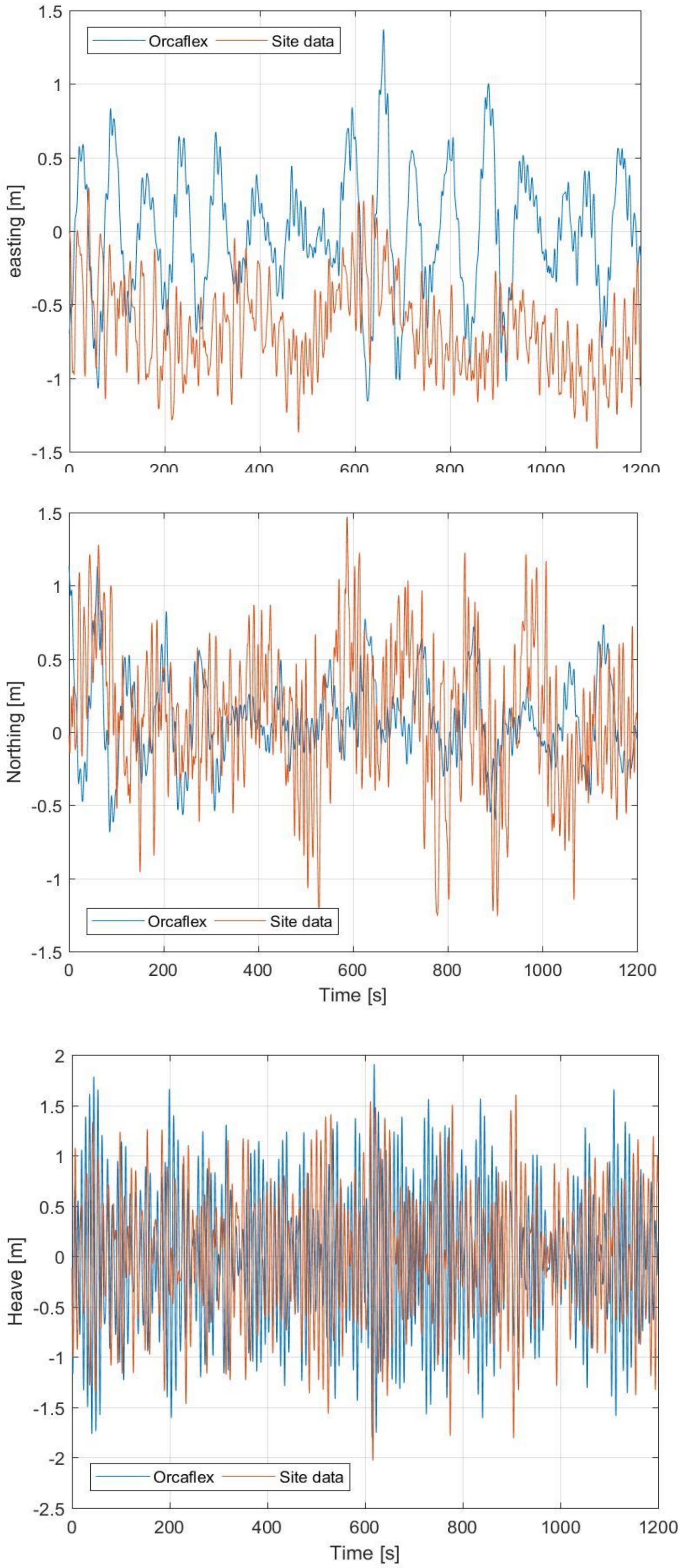


FIGURE. 10-4 TIME TRACE – MEDIUM ENVIRONMENT - ENV101P2

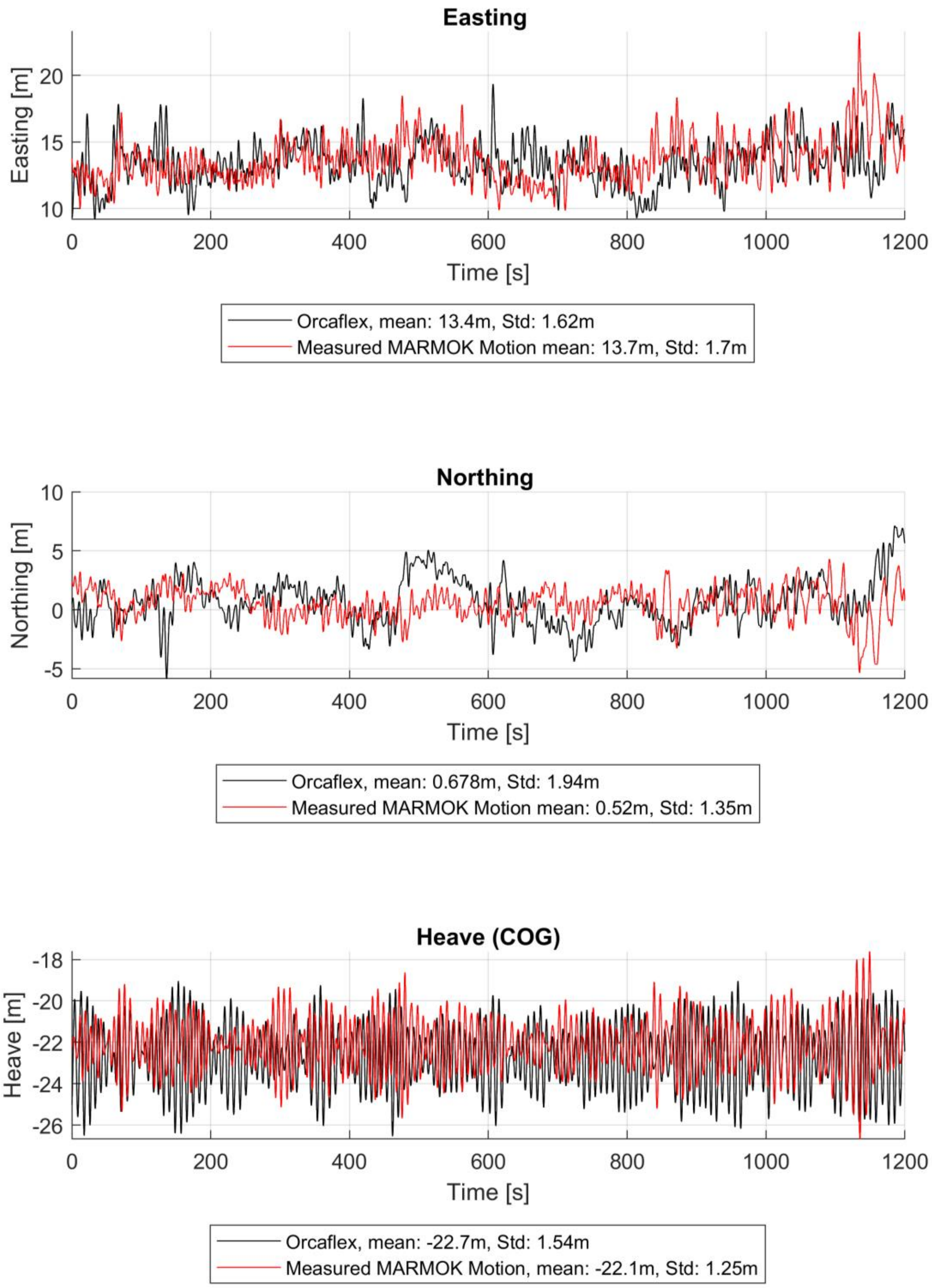


FIGURE. 10-5 TIME TRACE – ENV102P1

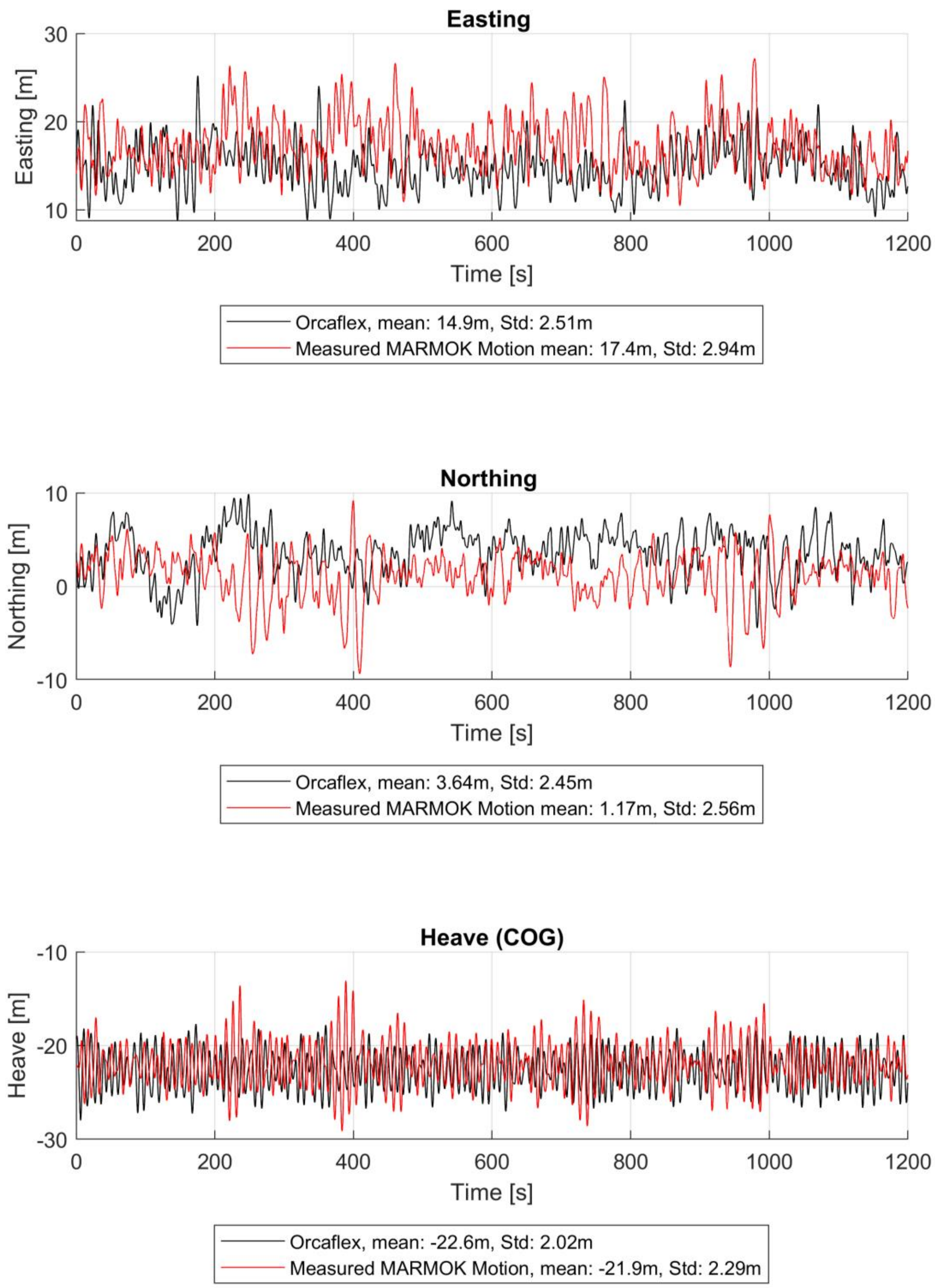


FIGURE. 10-6 TIME TRACE – EXTREME ENVIRONMENT - ENV103P1

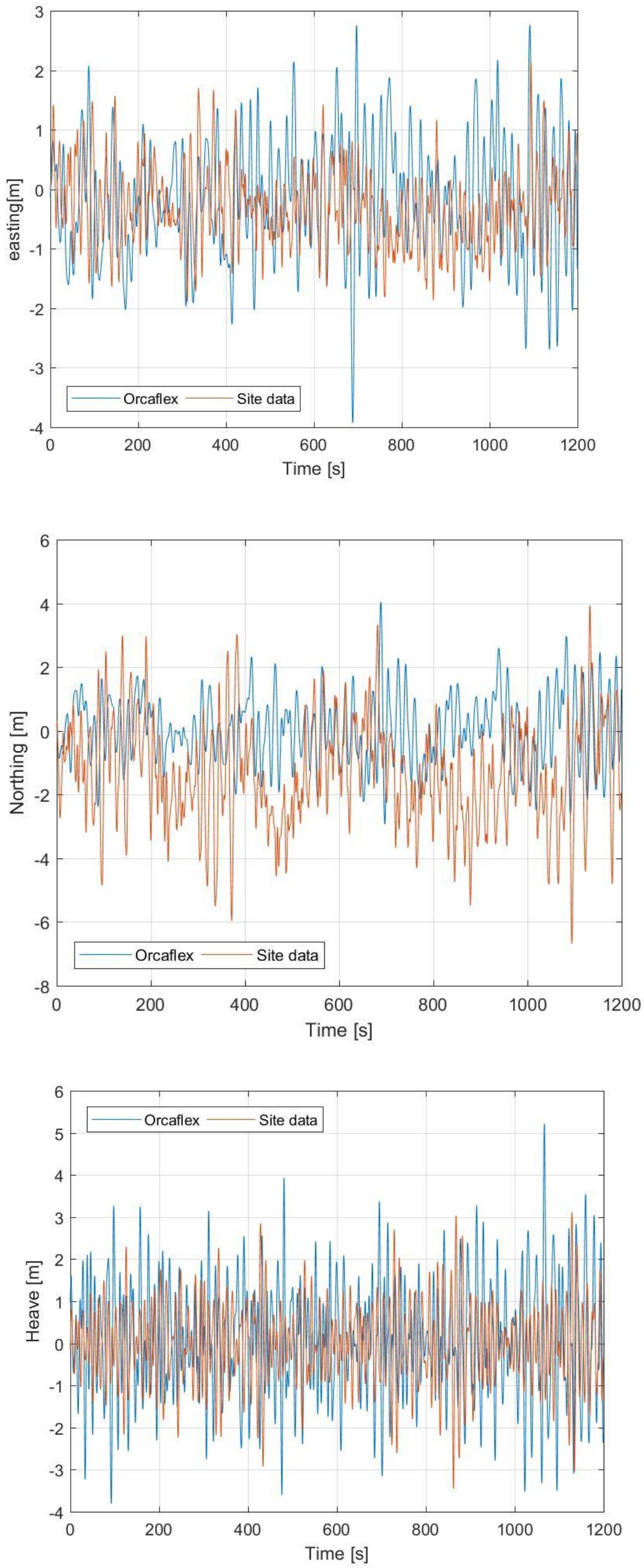


FIGURE. 10-7 TIME TRACE – EXTREME ENVIRONMENT - ENV103P2

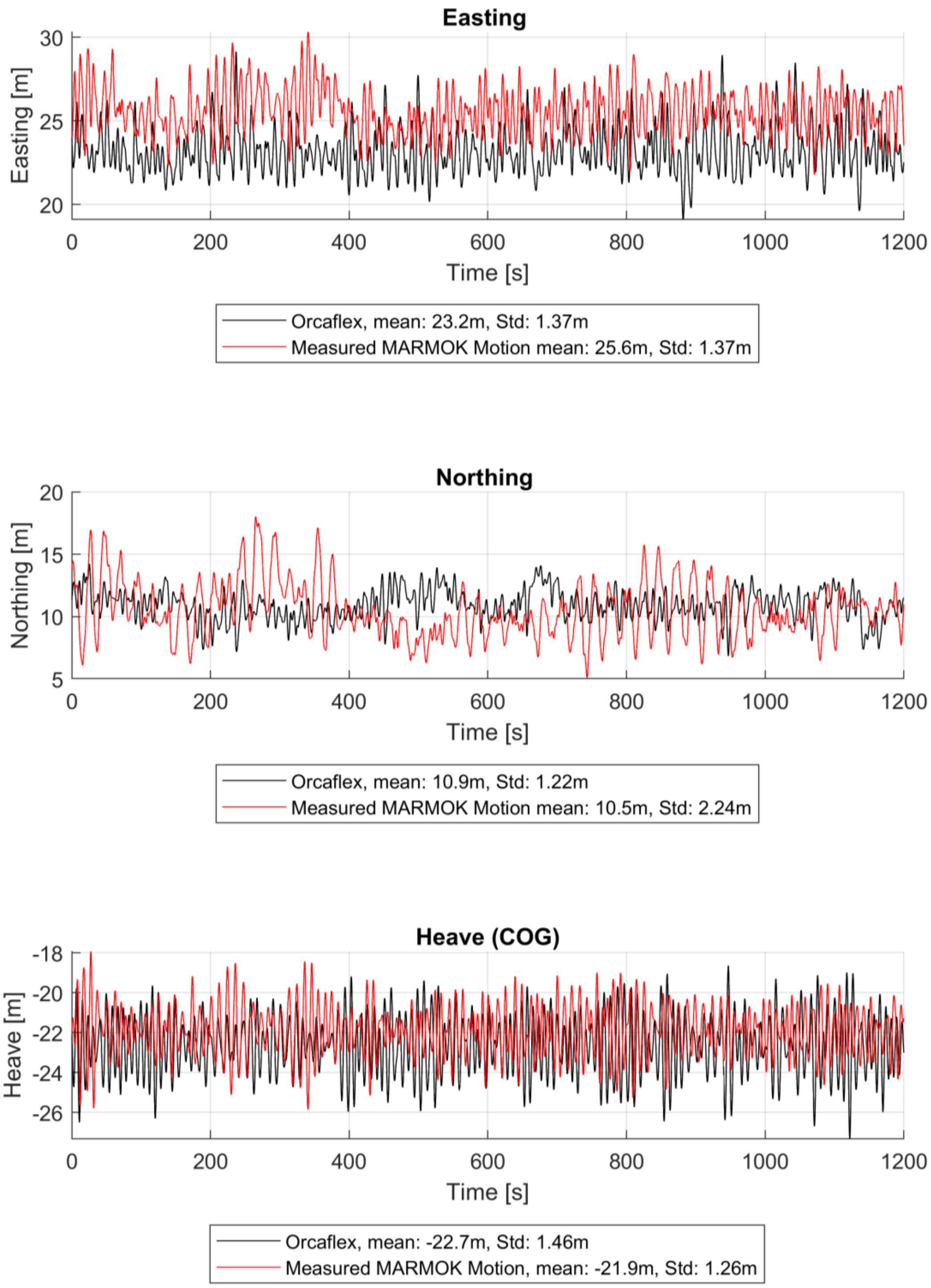


FIGURE. 10-8 TIME TRACE – ENV104P1

11. ANNEX IV: EASTING, NORTHING SPECTRA OF DGPS & HEAVE MOTION SPECTRA OF COG

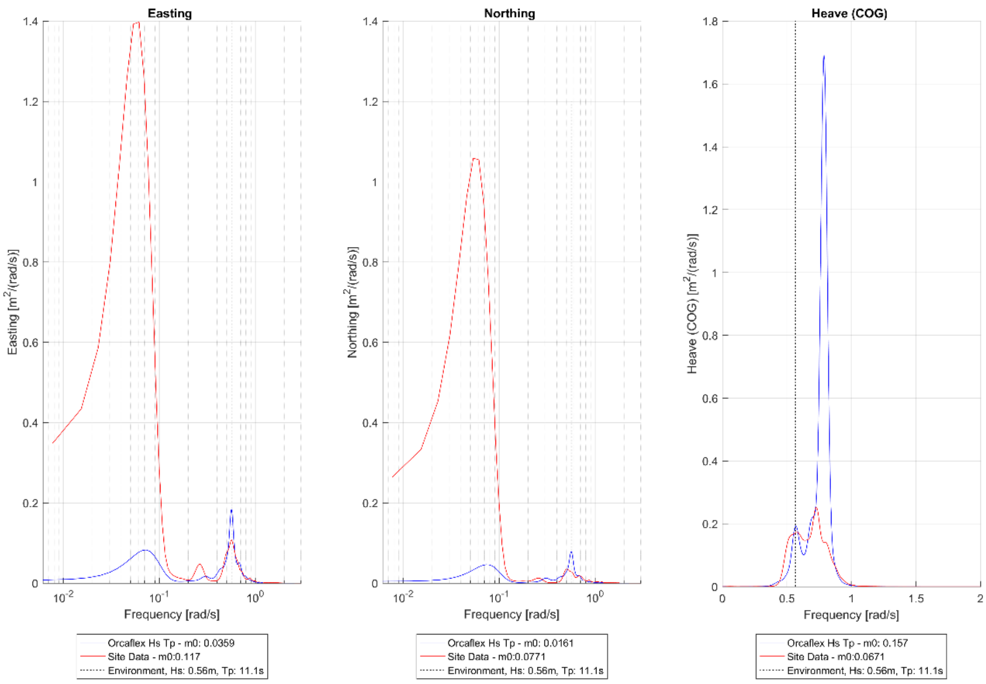


FIGURE. 11-1 MOTION SPECTRA – LOW ENVIRONMENT – ENV000P1

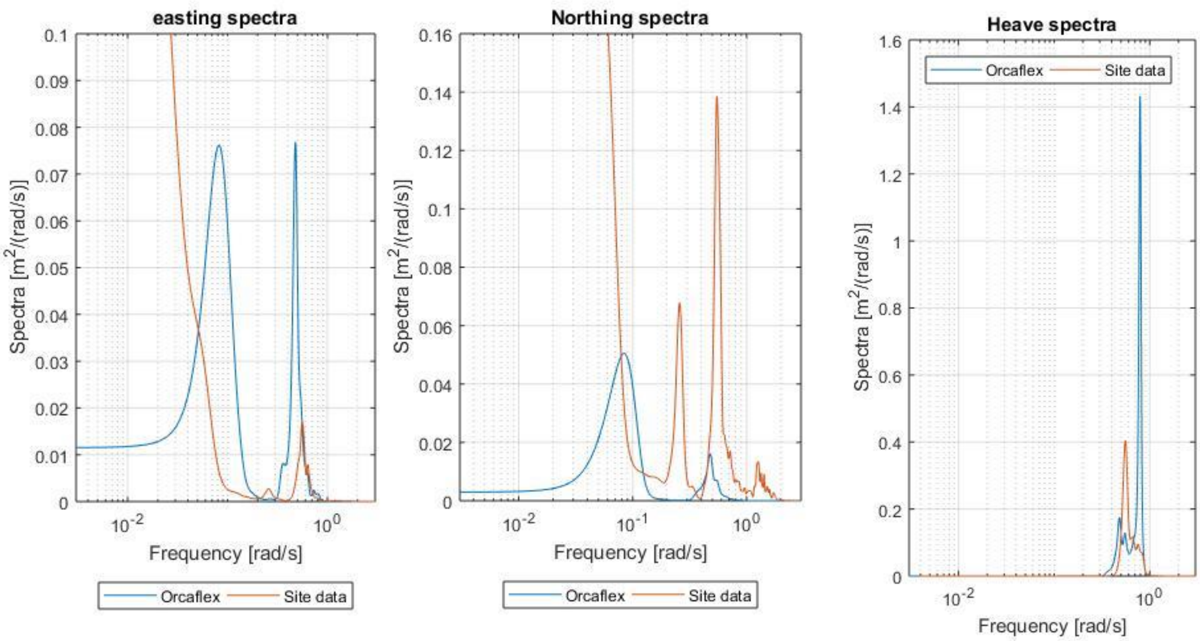


FIGURE. 11-2 MOTION SPECTRA – LOW ENVIRONMENT – ENV000P2

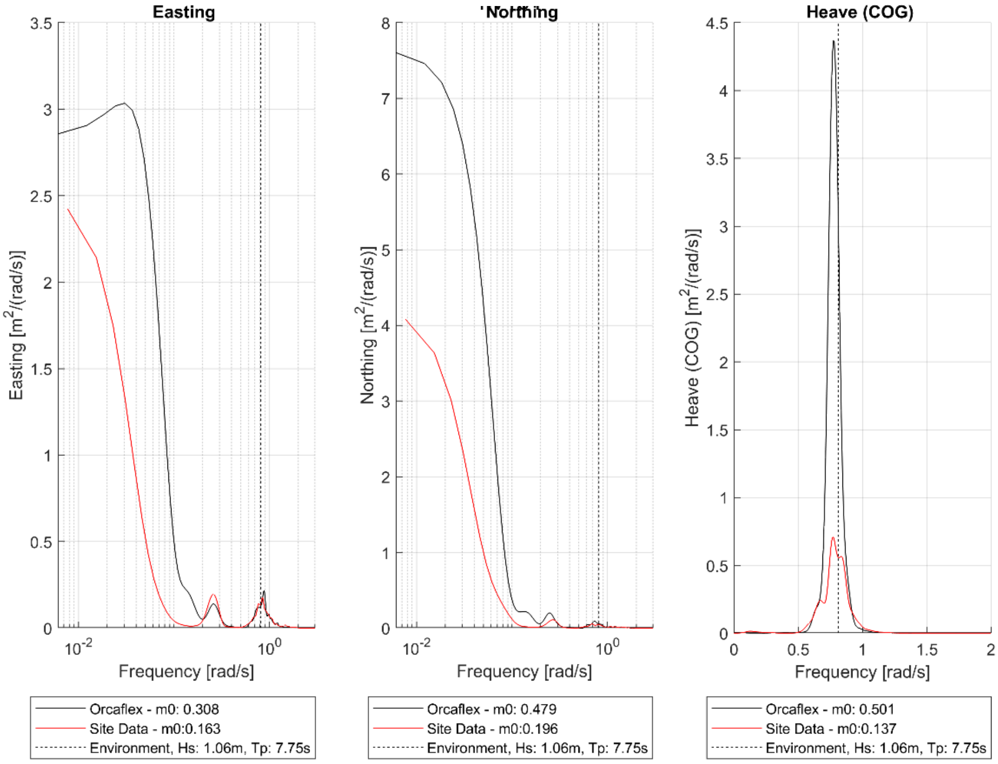


FIGURE. 11-3 MOTION SPECTRA– MEDIUM ENVIRONMENT - ENV101P1

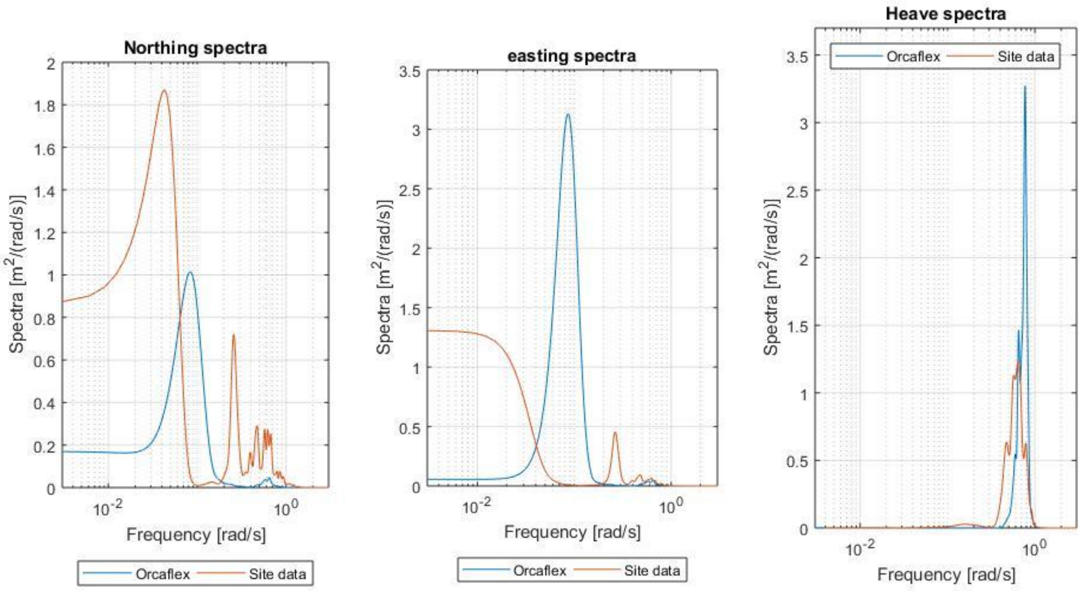


FIGURE. 11-4 MOTION SPECTRA– MEDIUM ENVIRONMENT - ENV101P2

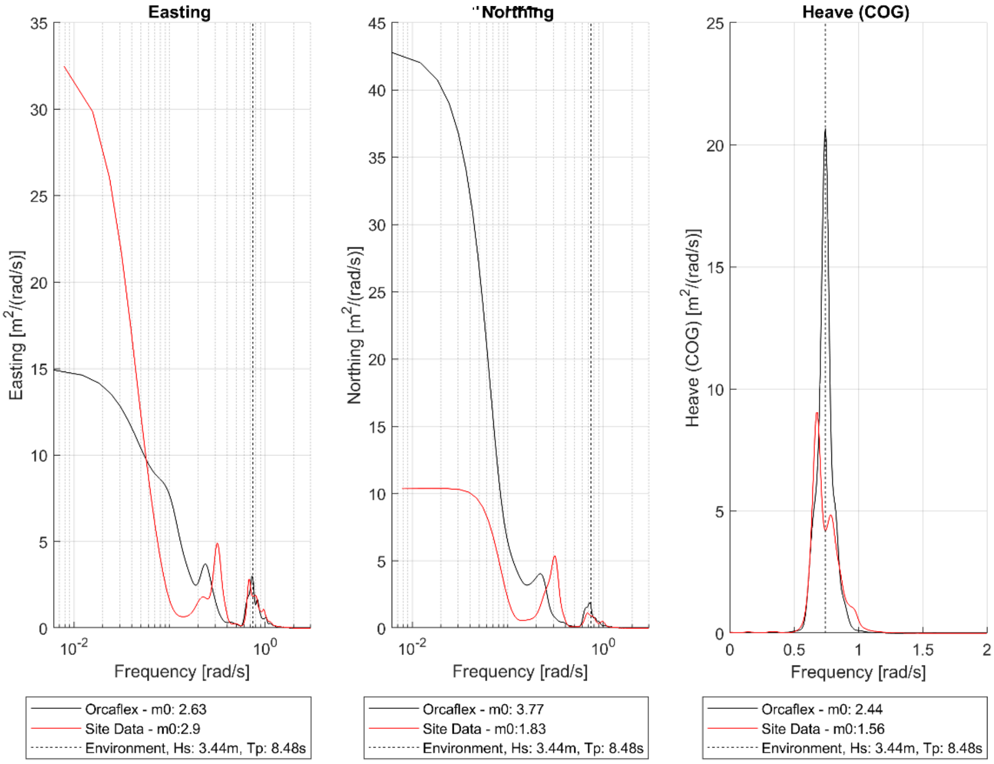


FIGURE. 11-5 MOTION SPECTRA – ENV102P1

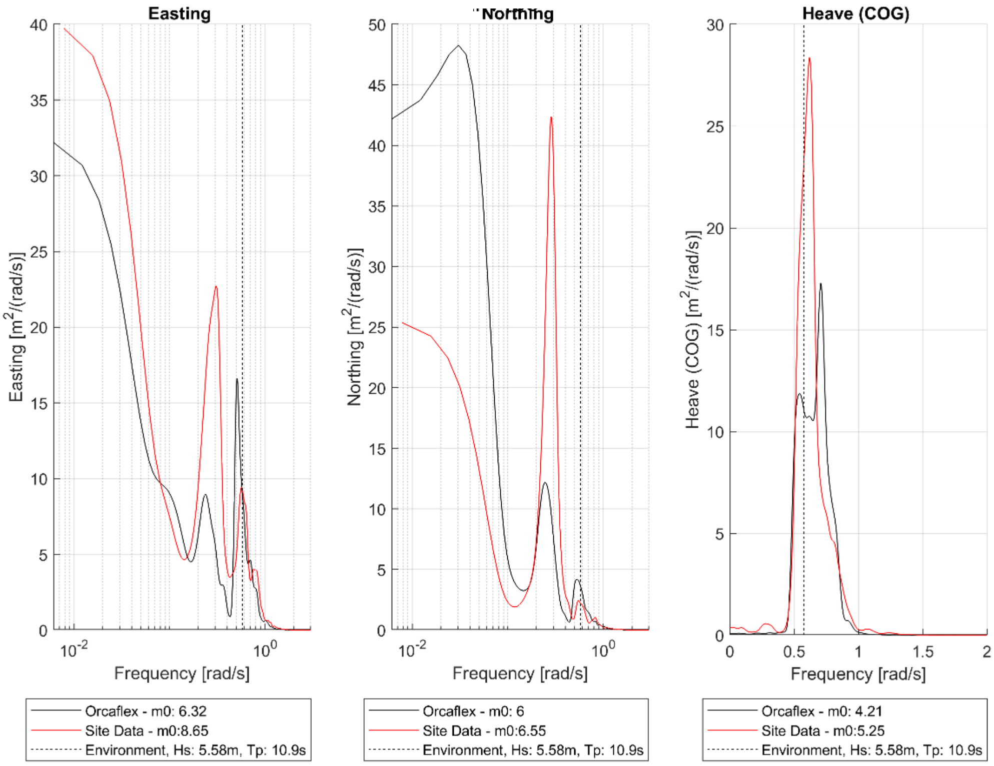


FIGURE. 11-6 MOTION SPECTRA– EXTREME ENVIRONMENT - ENV103P1

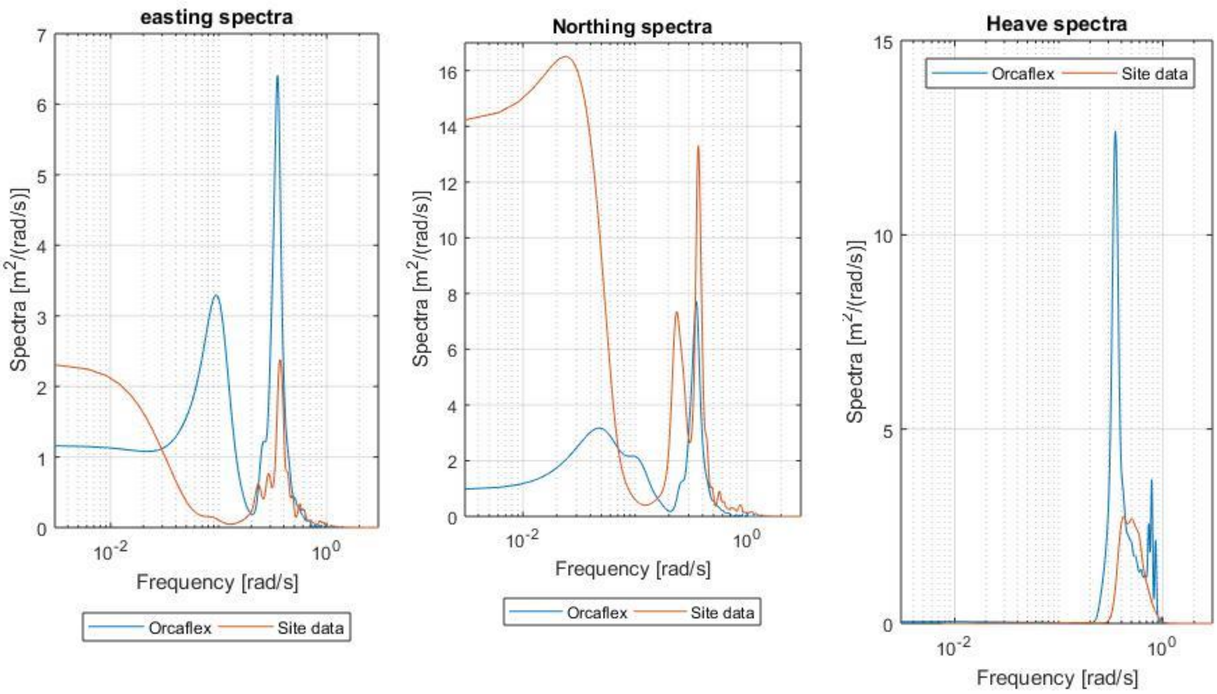


FIGURE. 11-7 MOTION SPECTRA– EXTREME ENVIRONMENT - ENV103P2

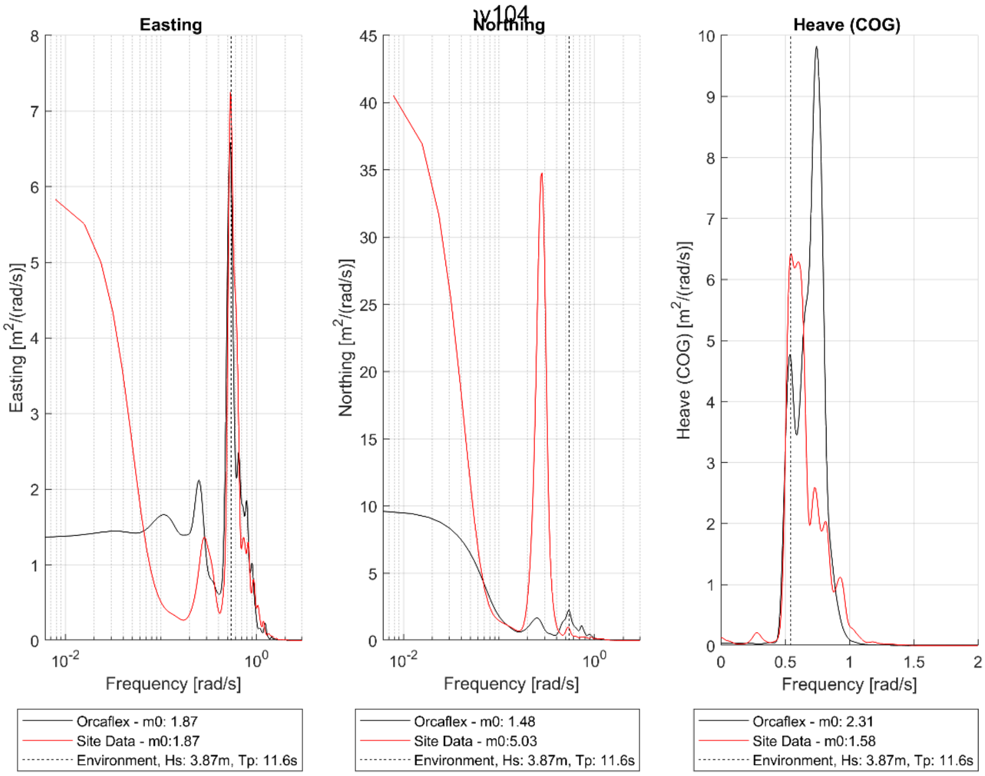


FIGURE. 11-8 MOTION SPECTRA – ENV104P1

12. ANNEX V: ROLL AND PITCH TIME TRACE AND SPECTRA

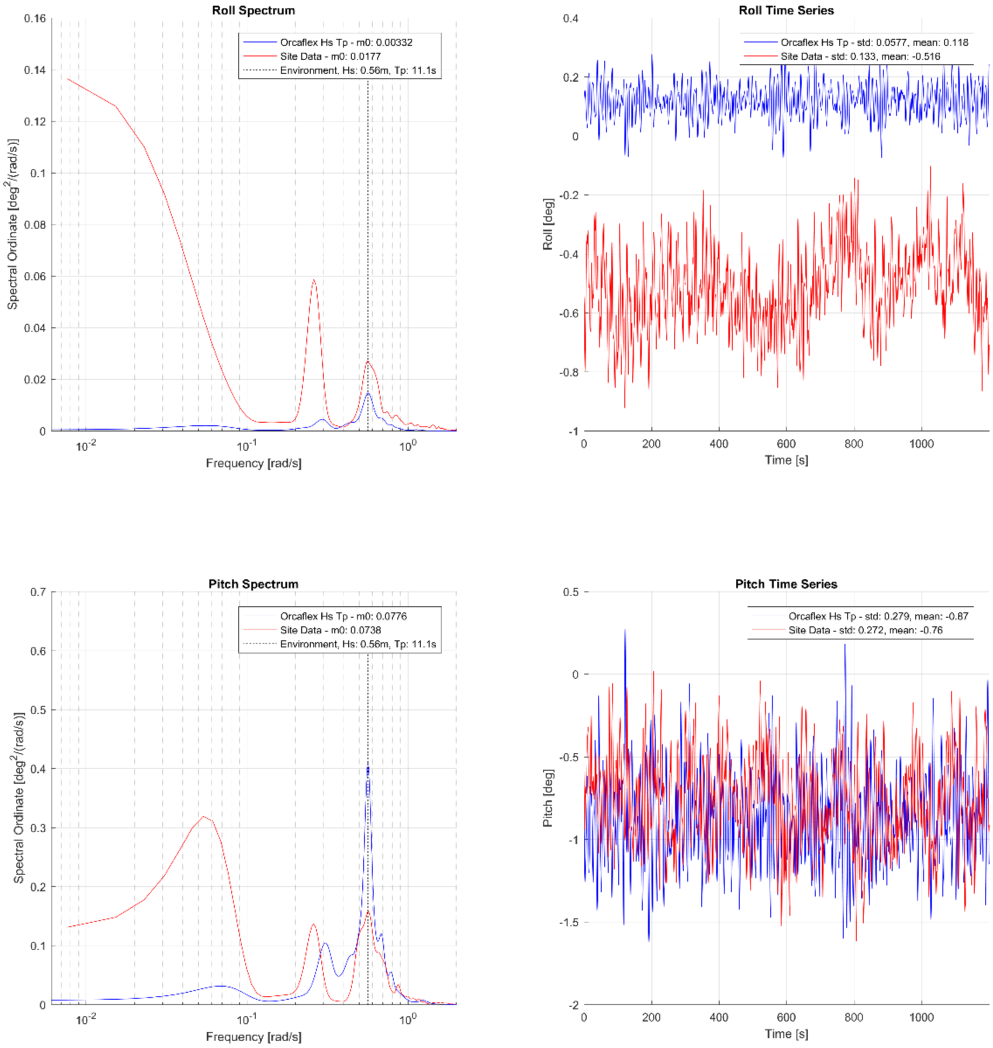


FIGURE. 12-1 ROLL AND PITCH – LOW ENVIRONMENT – ENV000P1

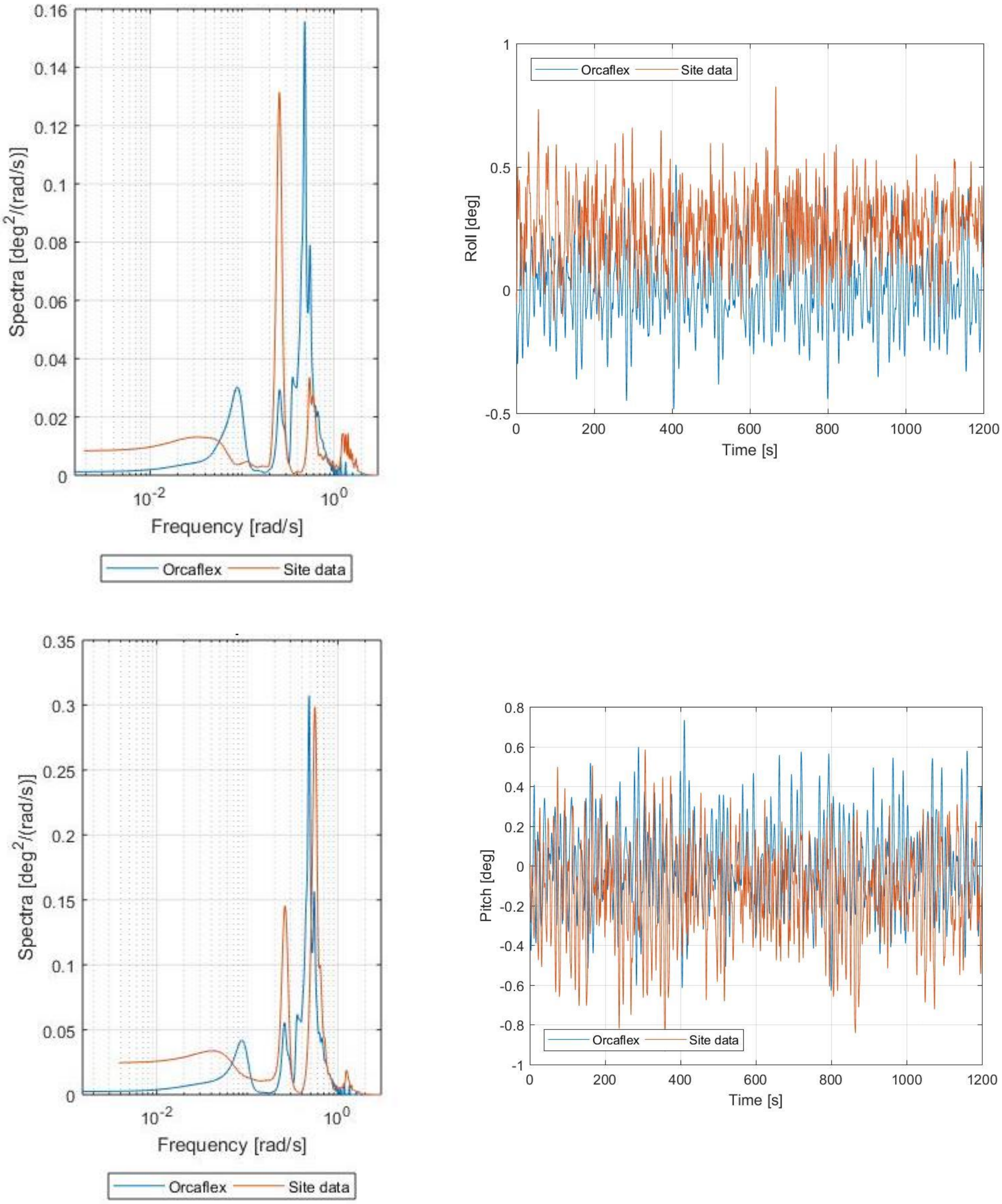


FIGURE. 12-2 ROLL AND PITCH – LOW ENVIRONMENT – ENV000P2

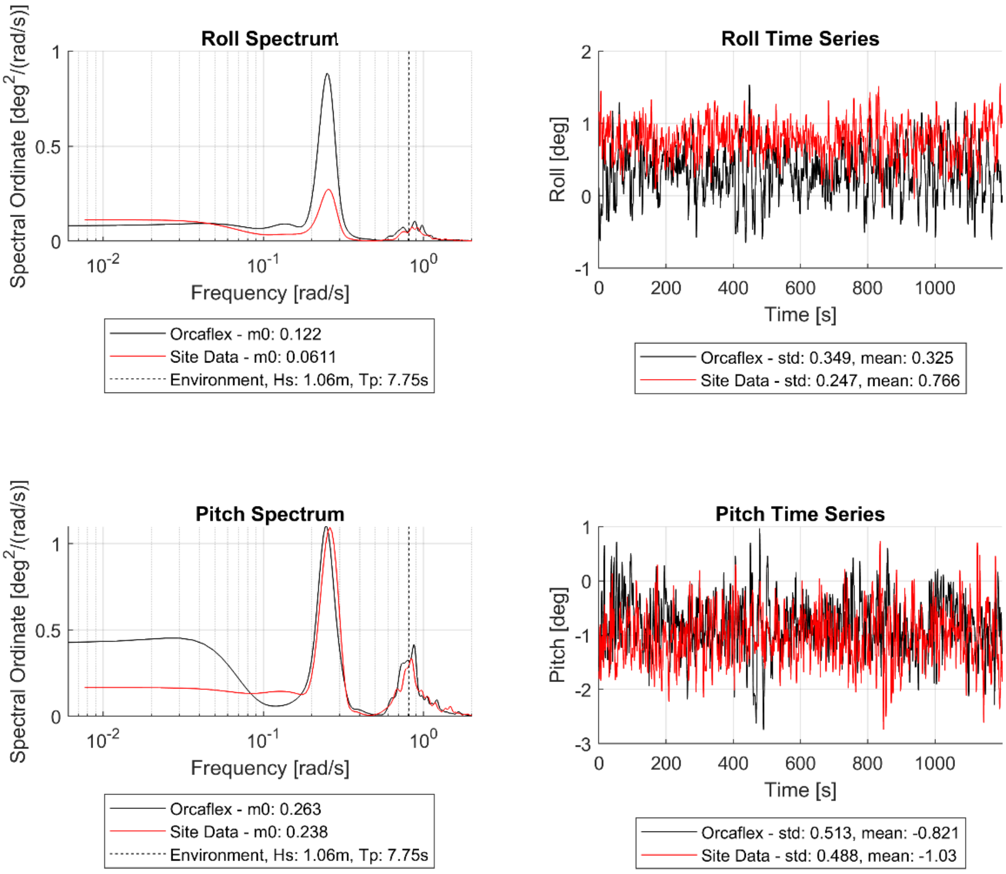


FIGURE. 12-3 ROLL AND PITCH – MEDIUM ENVIRONMENT - ENV101P1

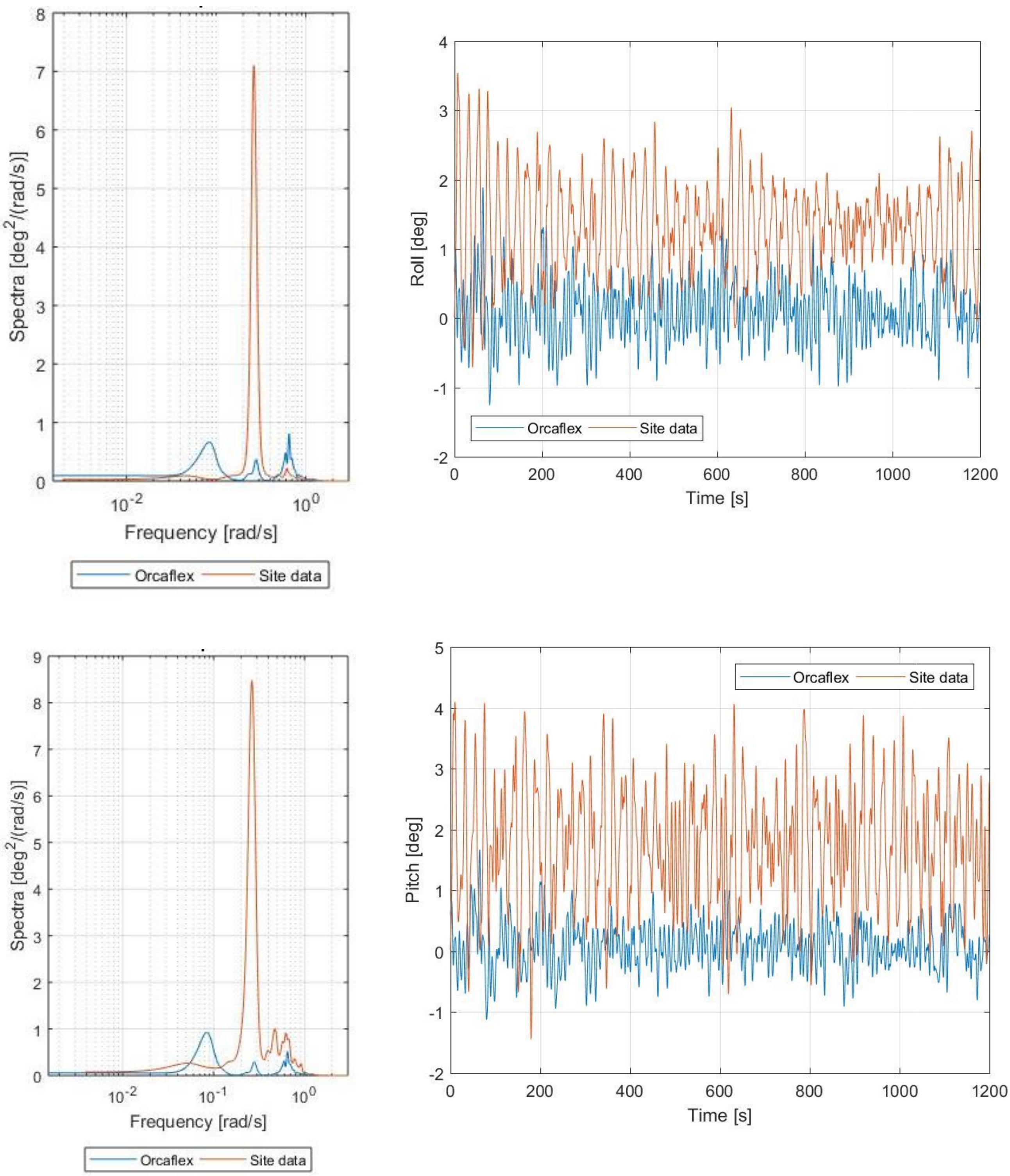


FIGURE. 12-4 ROLL AND PITCH – MEDIUM ENVIRONMENT - ENV101P2

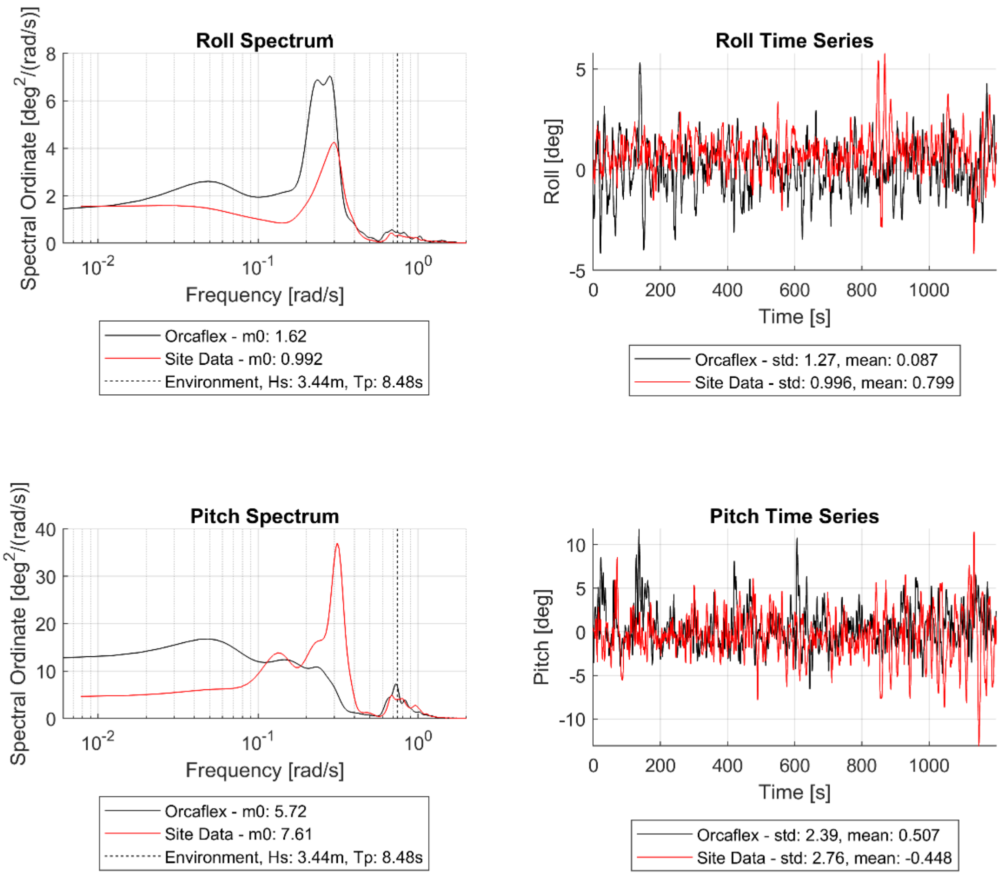


FIGURE. 12-5 ROLL AND PITCH – ENV102P1

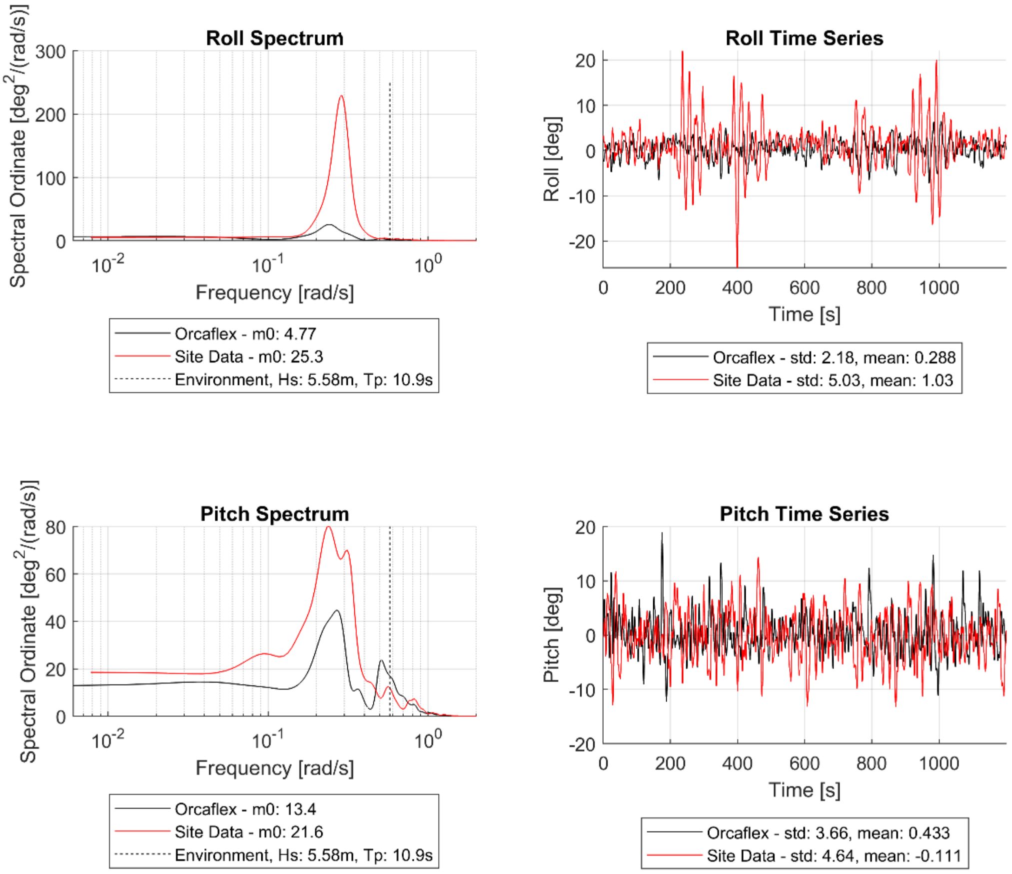


FIGURE. 12-6 ROLL AND PITCH – EXTREME ENVIRONMENT - ENV103P1

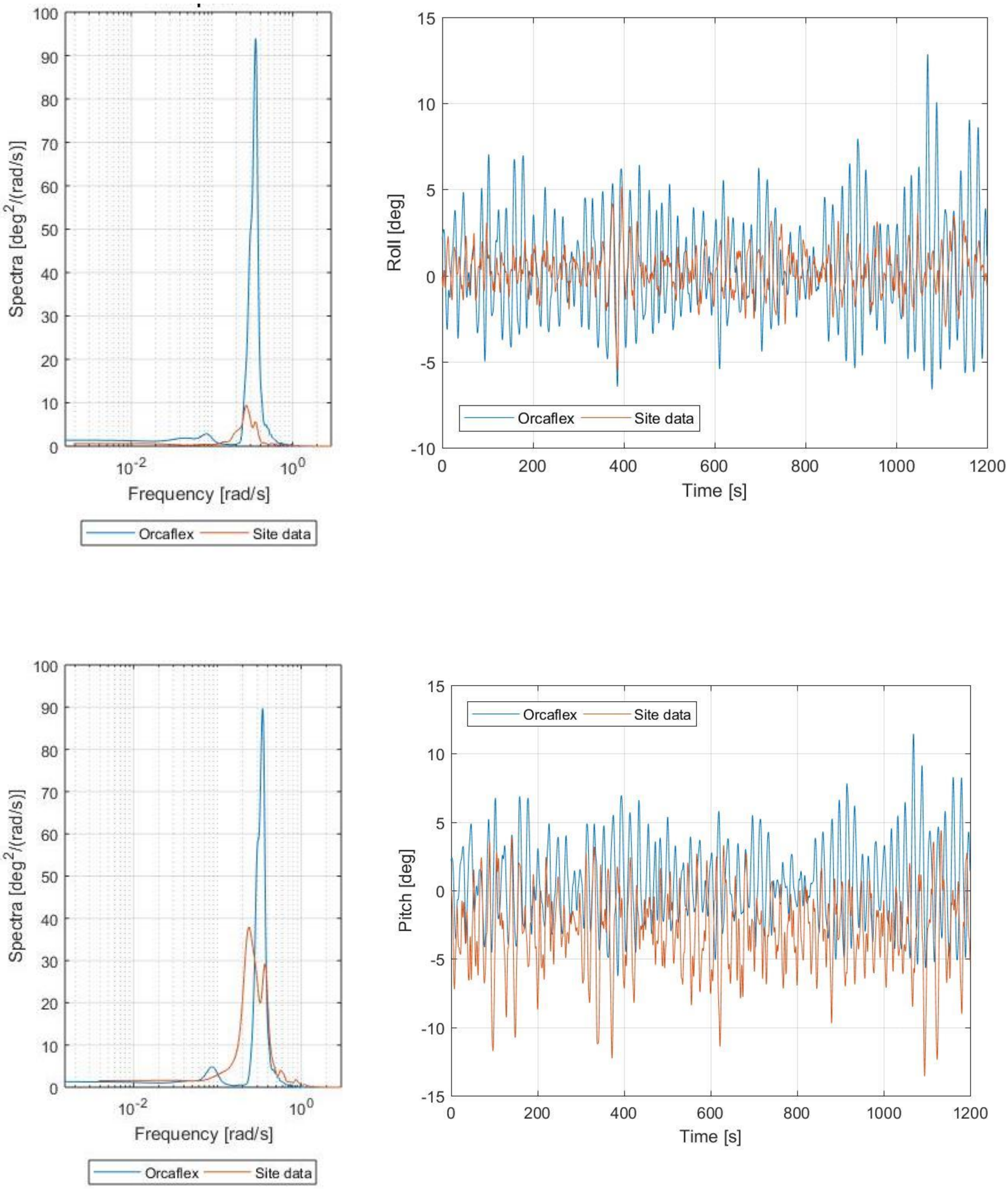


FIGURE. 12-7 ROLL AND PITCH – EXTREME ENVIRONMENT - ENV103P2

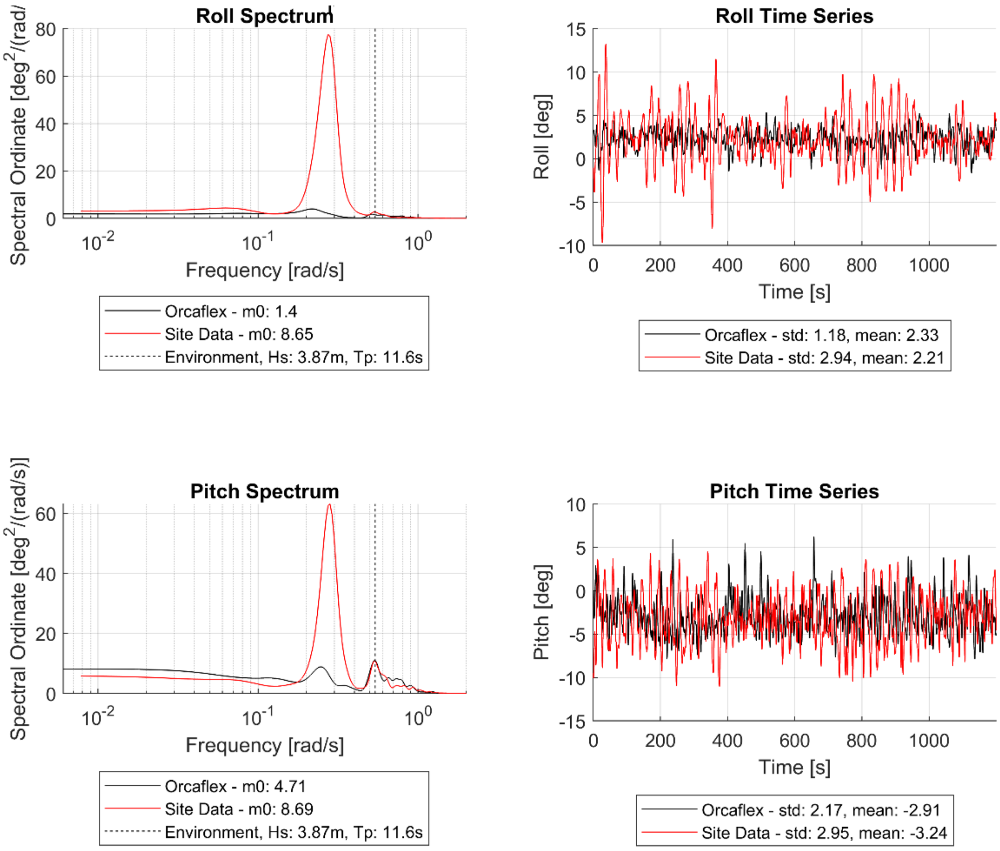


FIGURE. 12-8 ROLL AND PITCH – ENV104P1

13. ANNEX VI: SURGE AND SWAY PLOTS OF COG

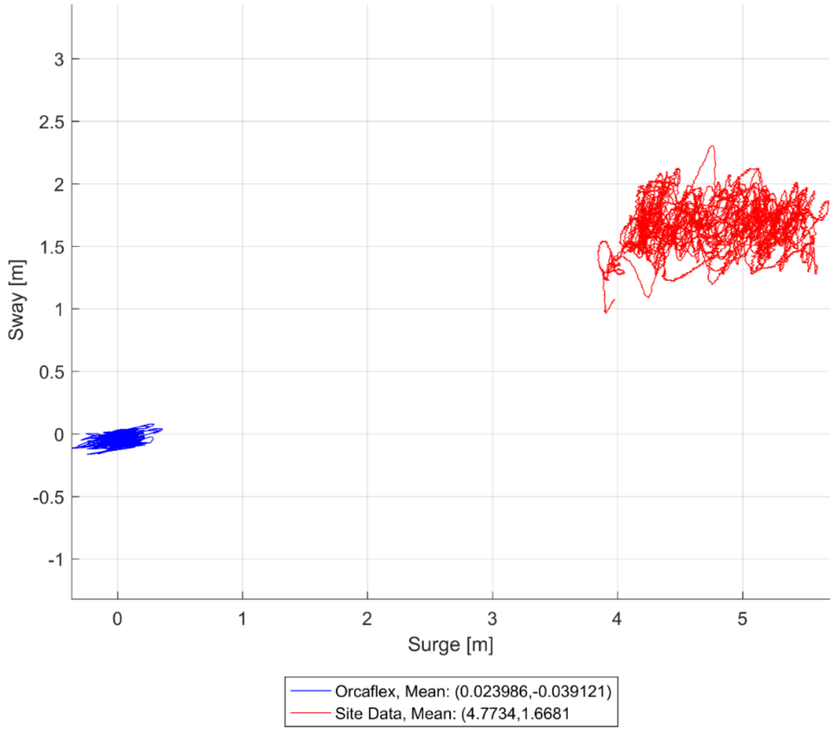


FIGURE. 13-1 SURGE AND SWAY OF COG – LOW ENVIRONMENT – ENV000P1

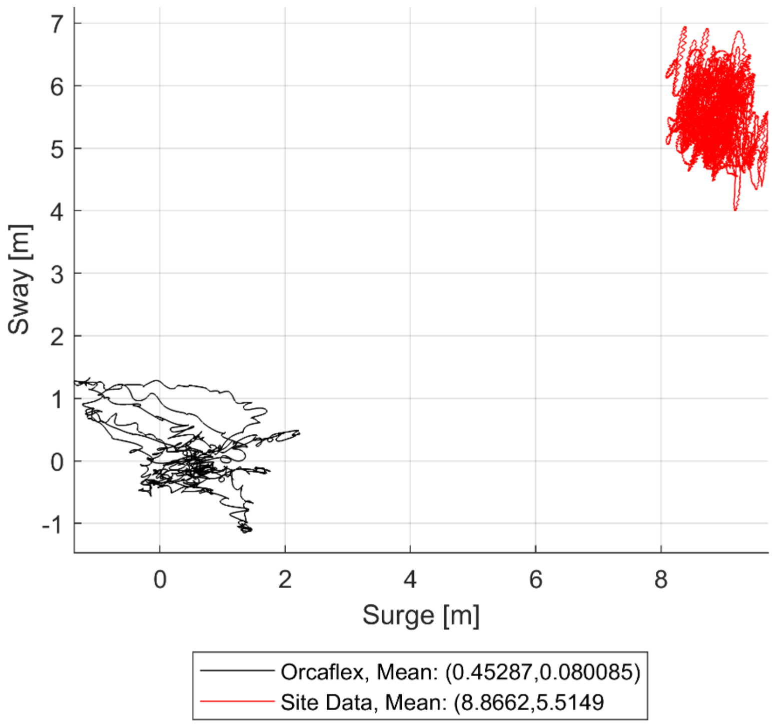


FIGURE. 13-2 SURGE AND SWAY OF COG – MEDIUM ENVIRONMENT - ENV101P1

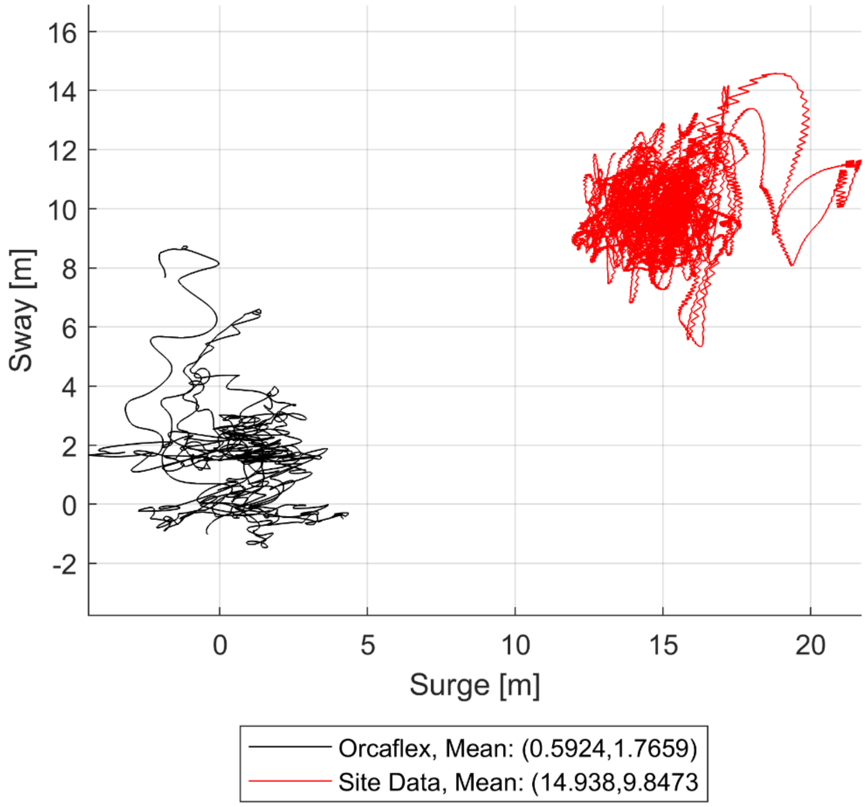


FIGURE. 13-3 SURGE AND SWAY OF COG – ENV102P1

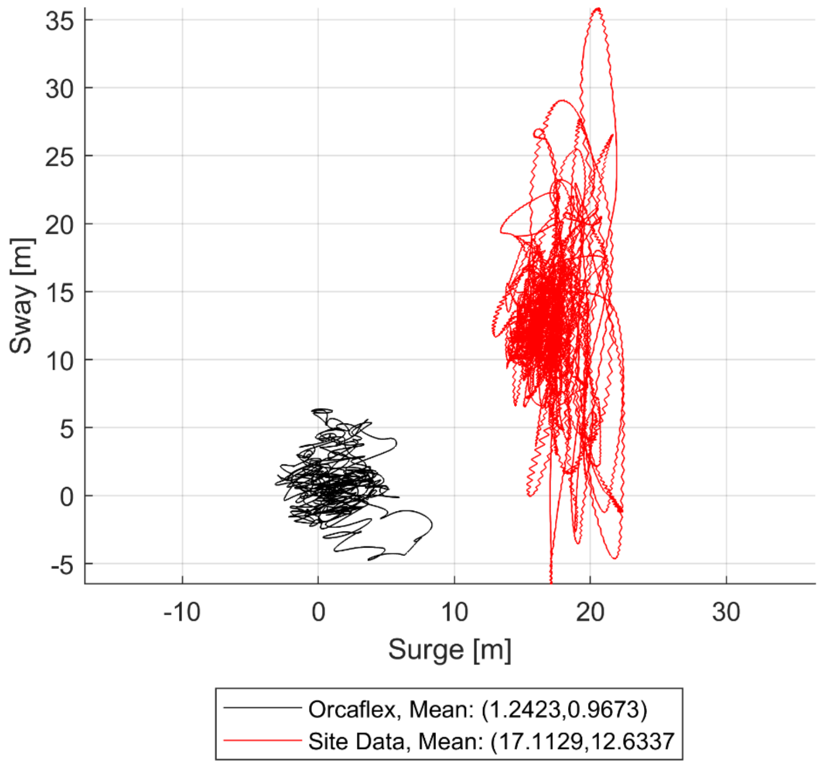


FIGURE. 13-4 SURGE AND SWAY OF COG – ENV103P1

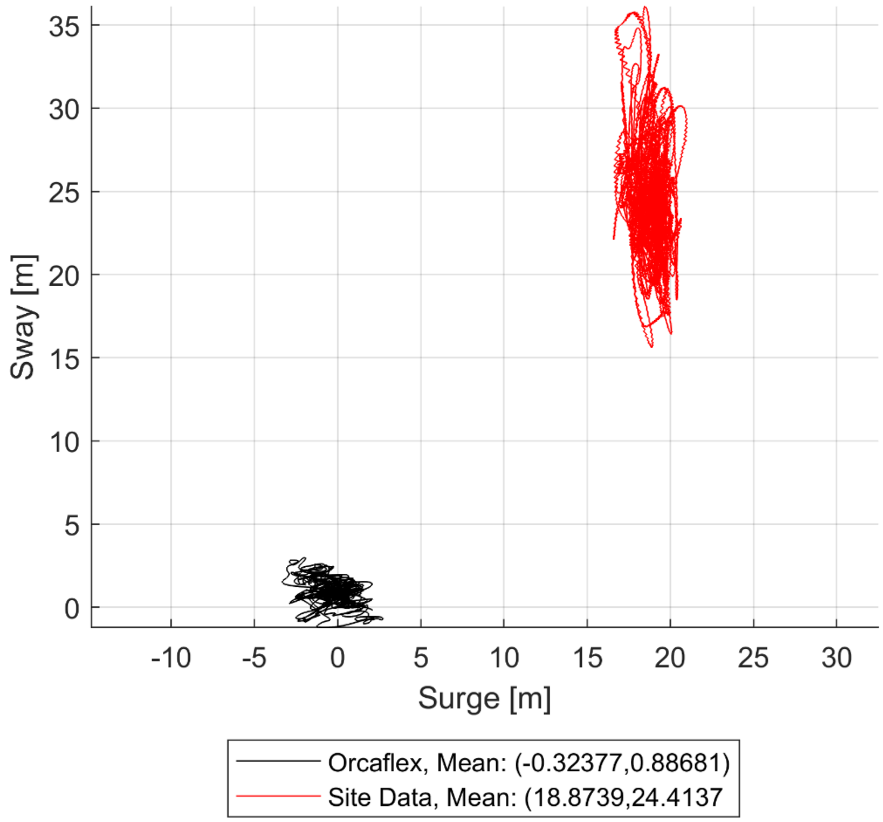


FIGURE. 13-5 SURGE AND SWAY OF COG – ENV104P1

14. ANNEX VII: TENSION TIME TRACE AND SPECTRA

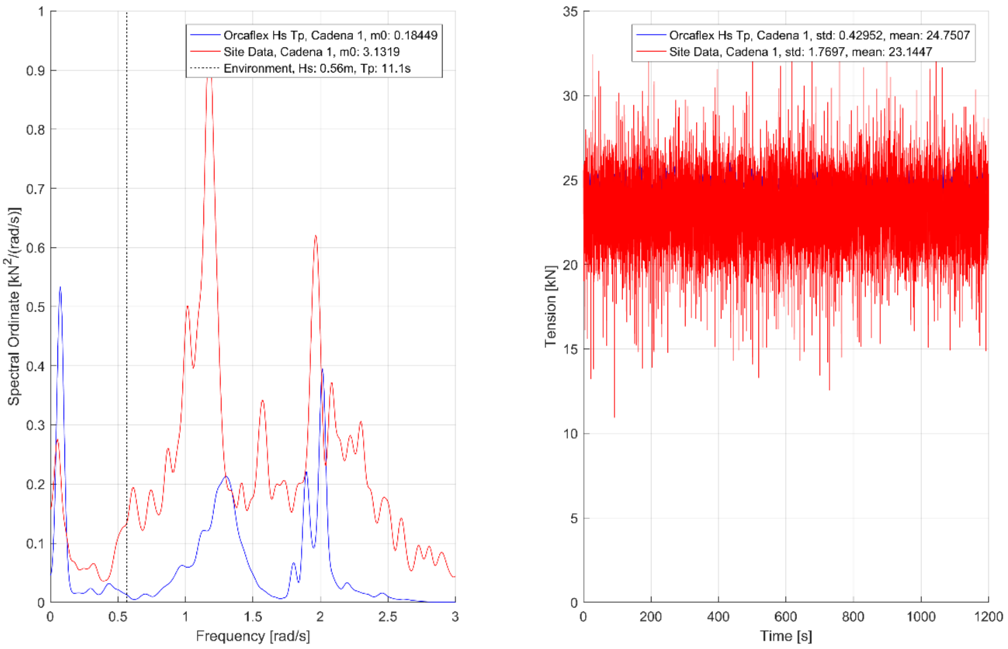


FIGURE. 14-1 TENSION TIME TRACE – LOW ENVIRONMENT – ENV000P2

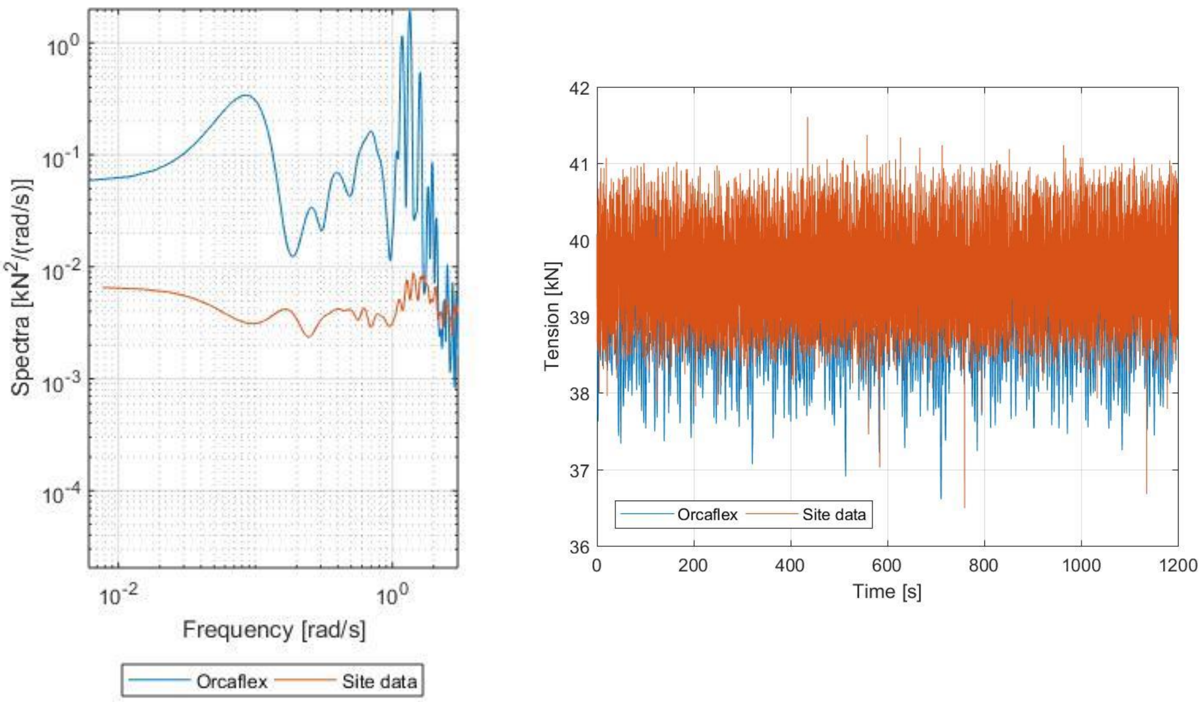


FIGURE. 14-2 TENSION TIME TRACE – LOW ENVIRONMENT – ENV000P1

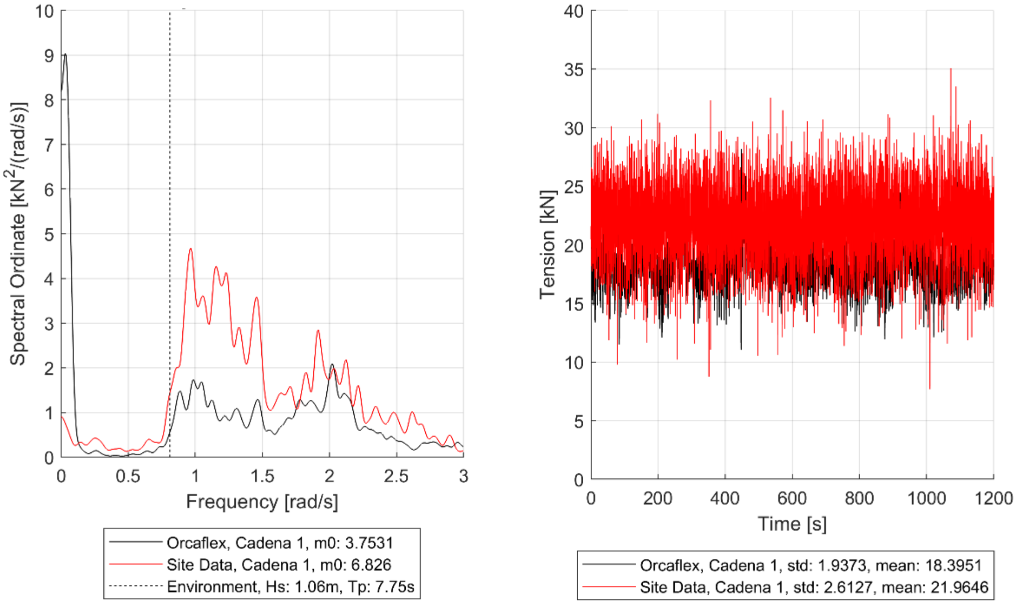


FIGURE. 14-3 TENSION TIME TRACE – MEDIUM ENVIRONMENT - ENV101P1

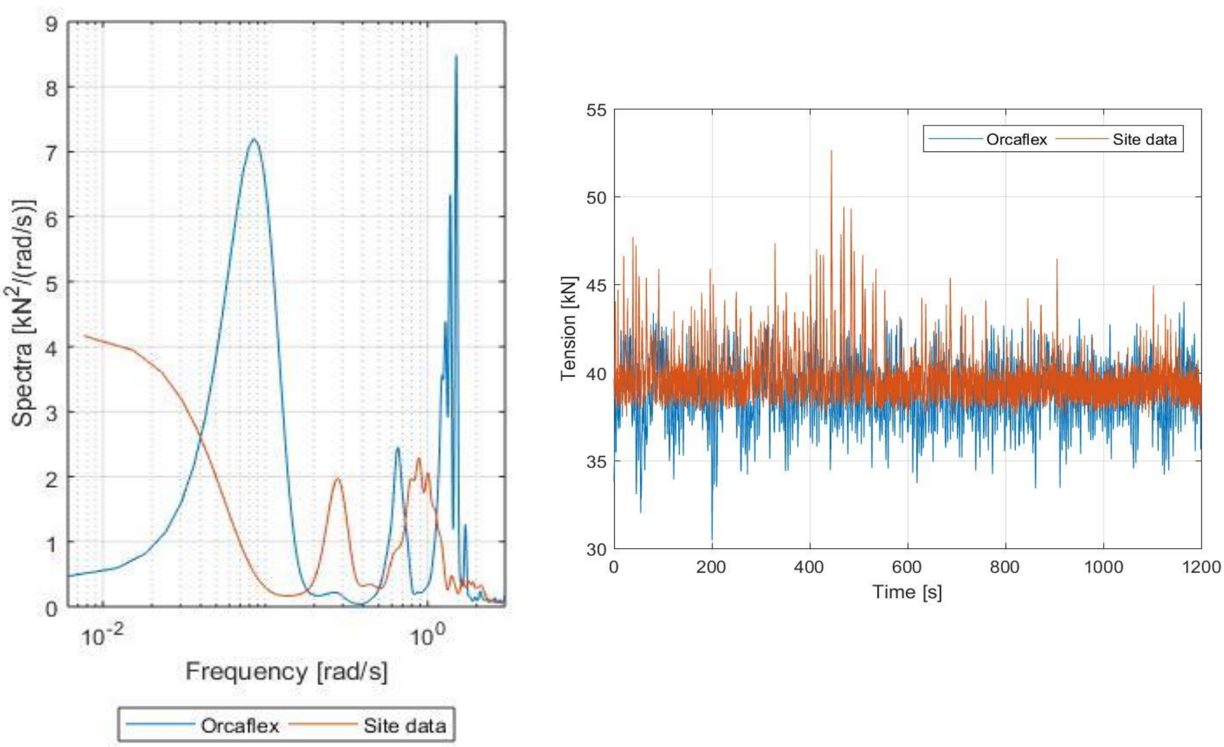


FIGURE. 14-4 TENSION TIME TRACE – MEDIUM ENVIRONMENT - ENV101P2

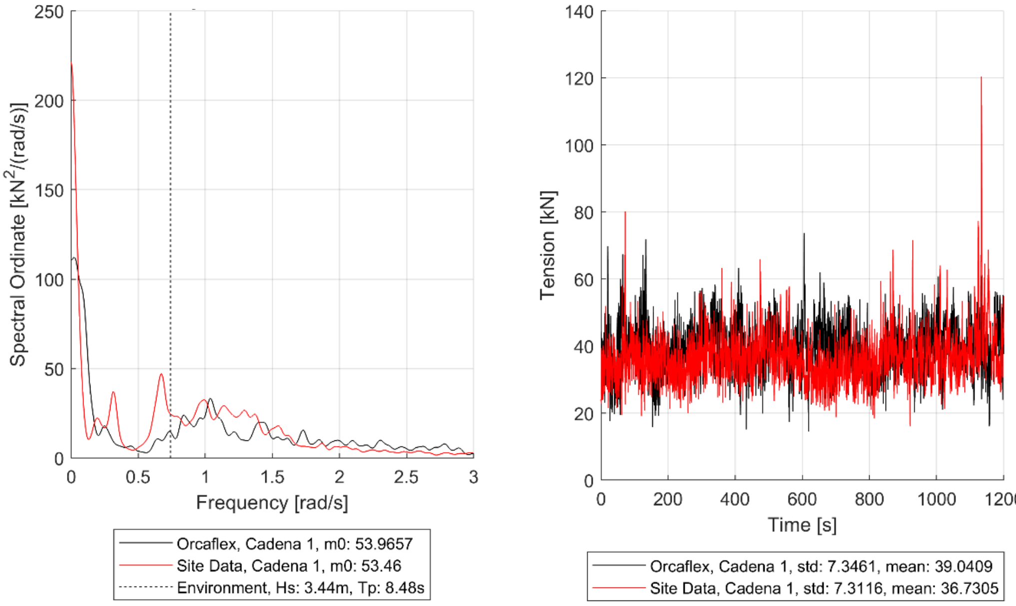


FIGURE. 14-5 TENSION TIME TRACE – ENV102P1

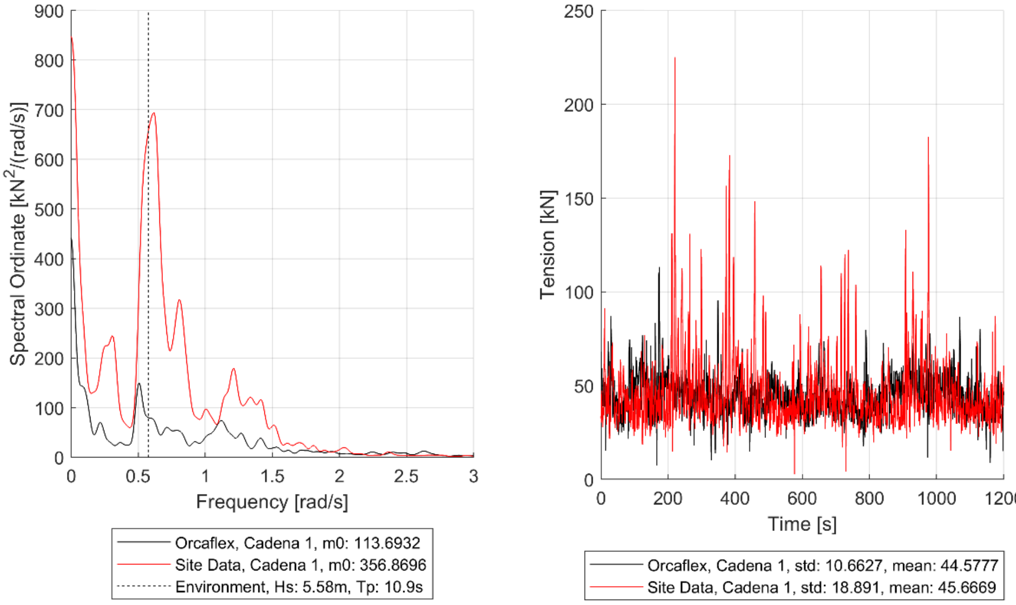


FIGURE. 14-6 TENSION TIME TRACE – EXTREME ENVIRONMENT - ENV103P1

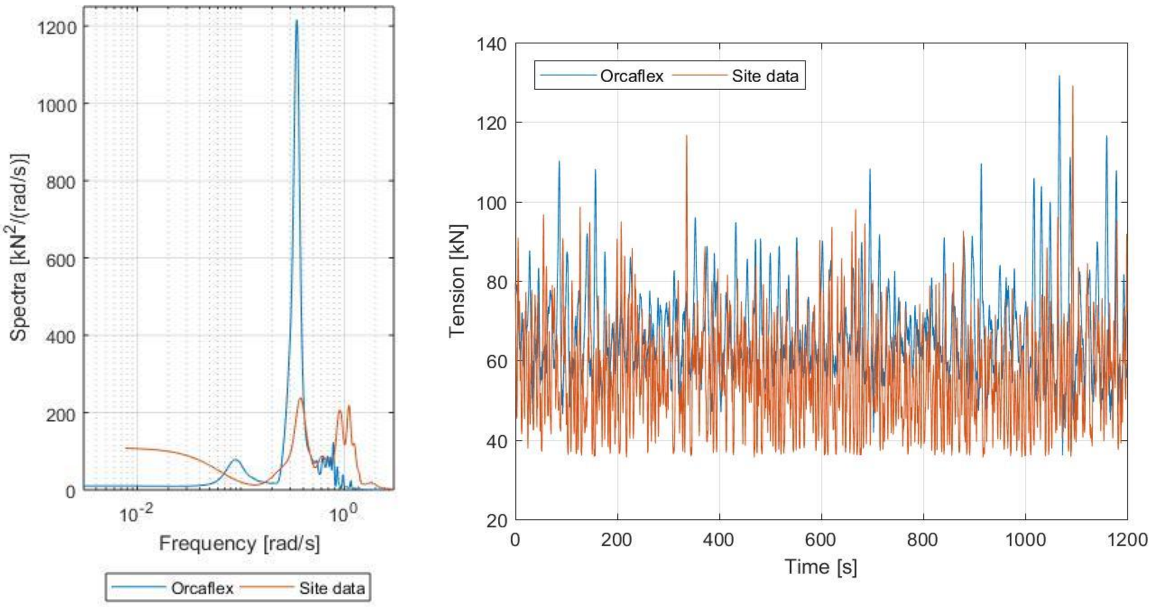


FIGURE. 14-7 TENSION TIME TRACE – EXTREME ENVIRONMENT - ENV103P2

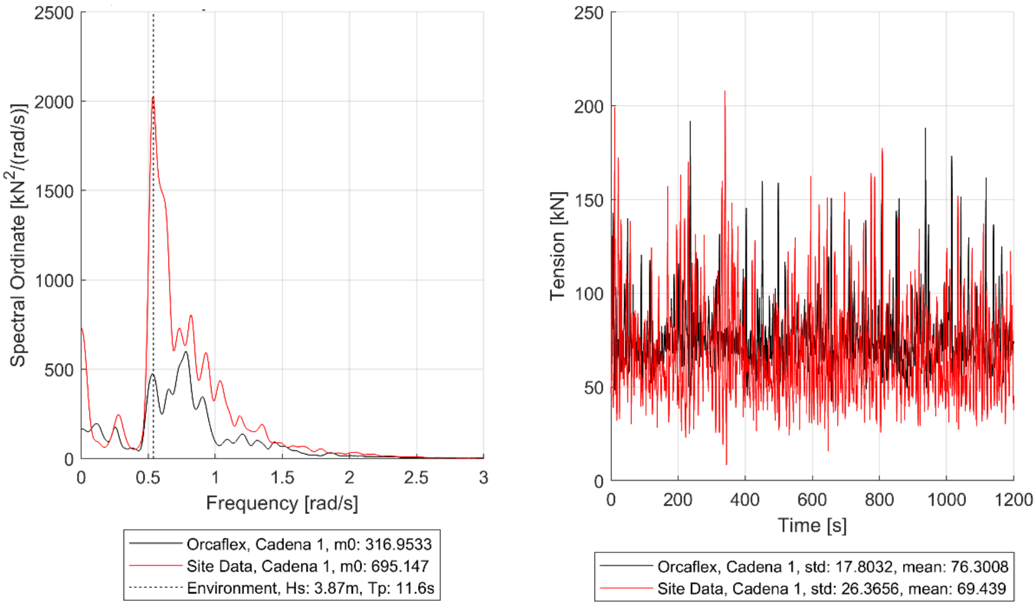


FIGURE. 14-8 TENSION TIME TRACE – ENV104P2

15. ANNEX VIII: DIRECTIONAL SPECTRA

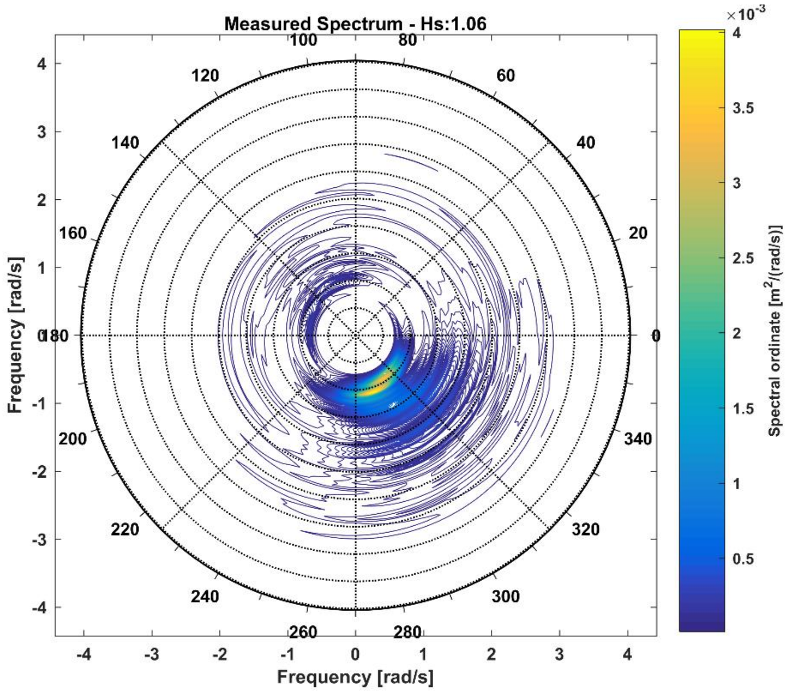


FIGURE. 15-1 MEASURED AND IDEALISED DIRECTIONAL SPECTRA – ENV101P1

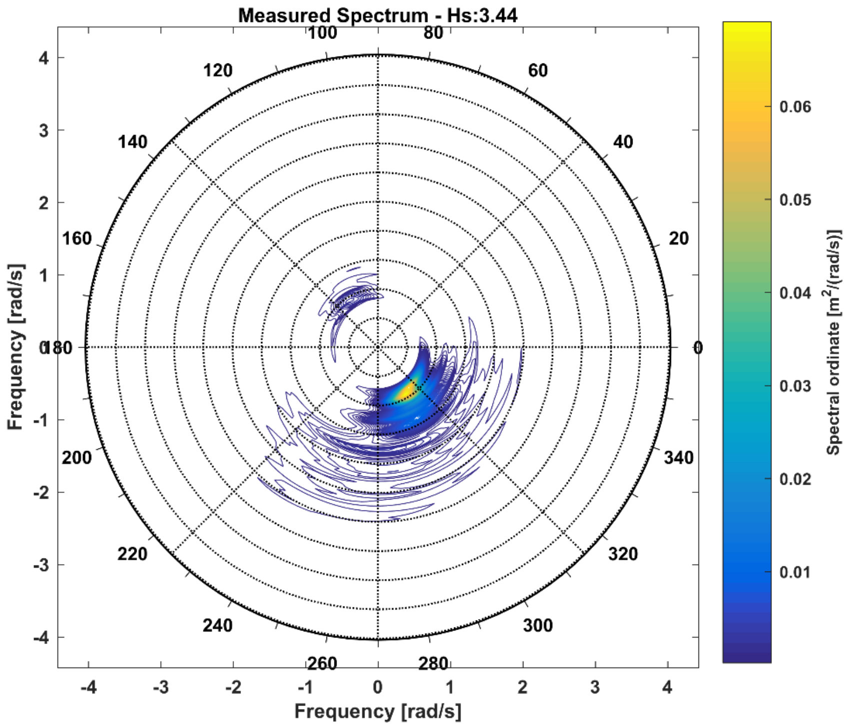


FIGURE. 15-2 MEASURED AND IDEALISED DIRECTIONAL SPECTRA - ENV102P1

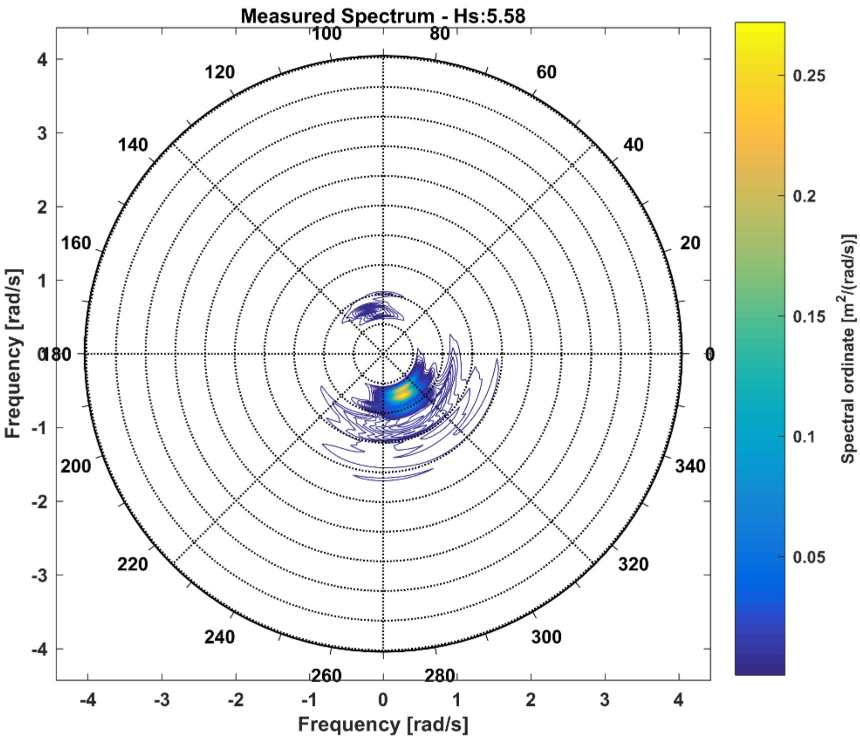


FIGURE. 15-3 MEASURED AND IDEALISED DIRECTIONAL SPECTRA - ENV103P1

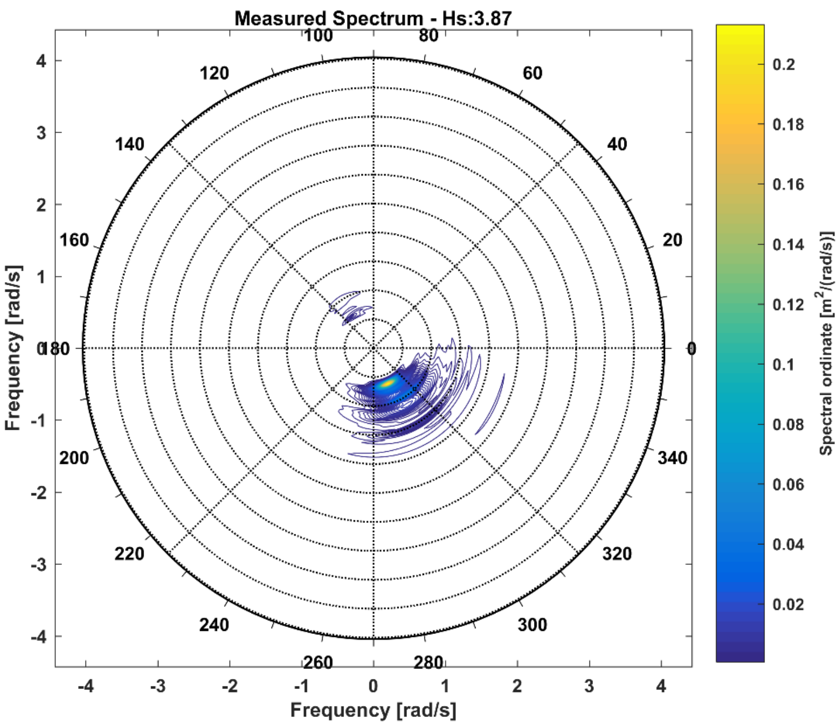


FIGURE. 15-4 MEASURED AND IDEALISED DIRECTIONAL SPECTRA - ENV104P1

16. ANNEX IX: CURRENT PROFILES

Current profiles from the ADCP is presented below, note that the ADCP has provided erroneous data close to the seabed which have resulted in "NaN".

Env101			Env102			Env102			Env102		
Depth [m]	Speed [m/s]	Direction [deg]	Depth [m]	Speed [m/s]	Direction [deg]	Depth [m]	Speed [m/s]	Direction [deg]	Depth [m]	Speed [m/s]	Direction [deg]
2.00	0.25	70.66	2.00	0.60	72.07	2.00	0.65	77.34	2.00	0.88	87.89
11.46	0.29	105.60	11.46	0.44	61.30	11.46	0.32	83.90	11.46	0.94	100.30
13.46	0.28	109.40	13.46	0.48	62.70	13.46	0.34	82.20	13.46	0.92	99.90
15.46	0.25	110.40	15.46	0.43	59.20	15.46	0.37	81.90	15.46	0.92	99.50
17.46	0.22	102.40	17.46	0.42	62.70	17.46	0.34	88.20	17.46	0.91	97.50
19.46	0.22	99.80	19.46	0.34	64.20	19.46	0.32	84.20	19.46	0.89	94.90
21.46	0.18	94.80	21.46	0.28	75.40	21.46	0.32	87.10	21.46	0.85	94.10
23.46	0.14	96.00	23.46	0.26	80.00	23.46	0.40	83.90	23.46	0.83	92.30
25.46	0.15	96.90	25.46	0.27	82.20	25.46	0.37	91.10	25.46	0.83	88.40
27.46	0.16	111.10	27.46	0.26	81.30	27.46	0.40	92.30	27.46	0.80	84.90
29.46	0.14	110.90	29.46	0.23	91.00	29.46	0.41	96.00	29.46	0.79	82.60
31.46	0.12	118.40	31.46	0.21	96.20	31.46	0.43	91.70	31.46	0.78	79.90
33.46	0.14	137.90	33.46	0.21	98.40	33.46	0.43	101.20	33.46	0.75	77.50
35.46	0.14	142.10	35.46	0.21	100.20	35.46	0.43	103.70	35.46	0.72	77.50
37.46	0.16	147.30	37.46	0.19	92.40	37.46	0.43	107.10	37.46	0.70	75.40
39.46	0.15	155.20	39.46	0.19	94.30	39.46	0.42	112.90	39.46	0.70	76.30
41.46	0.16	161.20	41.46	0.15	92.30	41.46	0.43	115.10	41.46	0.69	74.60
43.46	0.15	159.10	43.46	0.14	90.80	43.46	0.42	117.00	43.46	0.67	75.20
45.46	0.16	155.10	45.46	0.11	96.70	45.46	0.38	122.30	45.46	0.65	75.40
47.46	0.14	160.10	47.46	0.32	105.10	47.46	0.33	123.90	47.46	0.63	78.00
49.46	0.12	171.30	49.46	0.34	102.30	49.46	0.30	133.80	49.46	0.60	82.50
51.46	0.10	175.40	51.46	0.12	85.10	51.46	0.27	136.20	51.46	0.55	86.50
53.46	0.10	167.70	53.46	0.10	84.60	53.46	0.25	145.00	53.46	0.53	89.50
55.46	0.11	168.40	55.46	0.08	98.40	55.46	0.25	151.40	55.46	0.47	92.90
57.46	0.11	177.90	57.46	0.06	94.00	57.46	0.22	152.10	57.46	0.46	91.30
59.46	0.08	-178.60	59.46	0.05	90.00	59.46	0.33	116.70	59.46	0.29	88.60
61.46	0.07	-169.80	61.46	0.03	-118.60	61.46	0.32	111.50	61.46	0.29	100.10
63.46	0.07	-179.20	63.46	0.04	-25.30	63.46	0.36	107.40	63.46	0.19	108.00
65.46	0.08	177.00	65.46	0.14	-5.90	65.46	0.35	106.40	65.46	0.10	120.30
67.46	0.08	168.70	67.46	0.14	-69.40	67.46	0.43	97.80	67.46	NaN	NaN
69.46	0.13	174.50	69.46	NaN	NaN	69.46	0.40	-138.10	69.46	0.29	171.60
71.46	0.15	146.00	71.46	0.66	-87.00	71.46	NaN	NaN	71.46	NaN	NaN
73.46	0.23	-120.50	73.46	NaN	NaN	73.46	NaN	NaN	73.46	NaN	NaN
75.46	NaN	NaN	75.46	NaN	NaN	75.46	NaN	NaN	75.46	NaN	NaN
77.46	NaN	NaN	77.46	NaN	NaN	77.46	NaN	NaN	77.46	NaN	NaN

17. ANNEX X: SEASTATE CHARACTERISATION

This annex describes how the analytical JONSWAP spectrum has been fitted to the measured site spectrum. Moreover, the annex describes how a spreading function has been fitted to the measured directional spectrum.

JONSWAP Fitting

The non-fully developed sea state can be idealized using the JONSWAP spectrum, which is an expansion of the Pierson-Moskowitz spectrum, equation 1 [Ref 1].

$$\boldsymbol{S(f) = \frac{5}{16}\frac{H_s^2}{T_p^4 f^5} exp\left(-\frac{5}{4T_p^4 f^4}\right)} \qquad (1)$$

By modifying the Pierson-Moskowitz spectrum the JONSWAP spectrum can be defined as:

$$S_j(f) = \alpha \frac{H_s^2}{T_p^4 f^5} \exp\left(-\frac{5}{4T_p^4 f^4}\right)\gamma^r \qquad (2)$$

Where:

$$r = \exp\left(-\frac{(T_p f-1)^2}{2\sigma^2}\right) \qquad (3)$$

$$\alpha = \frac{0.0624}{0.23+0.0336\gamma-0.185(1.9+\gamma)^{-1}} \qquad (4)$$

$$\sigma = \begin{cases} 0.07, & f \le f_p \\ 0.09, & f > f_p \end{cases} \qquad (5)$$

here T_p is the peak period, H_s is the significant wave height, and "g" the gravitational constant. The parameter γ is sometimes referred to as the spectrum peakness coefficient. From the measured data Hs and Tp are known values and the only unknow variable is γ.

The fitting of is γ was based on the minimisation of the root mean square error, computed as:

$$e_{rms} = \left(\frac{\sum_{i=1}^{N}\left(S_m(f_i)-S_j(f_i)\right)^2}{N}\right)^{0.5} \qquad (6)$$

Where S_m denotes the measured spectral ordinates.

Figure. 17-1 shows an example of a fitted JONSWAP and the measured spectrum.

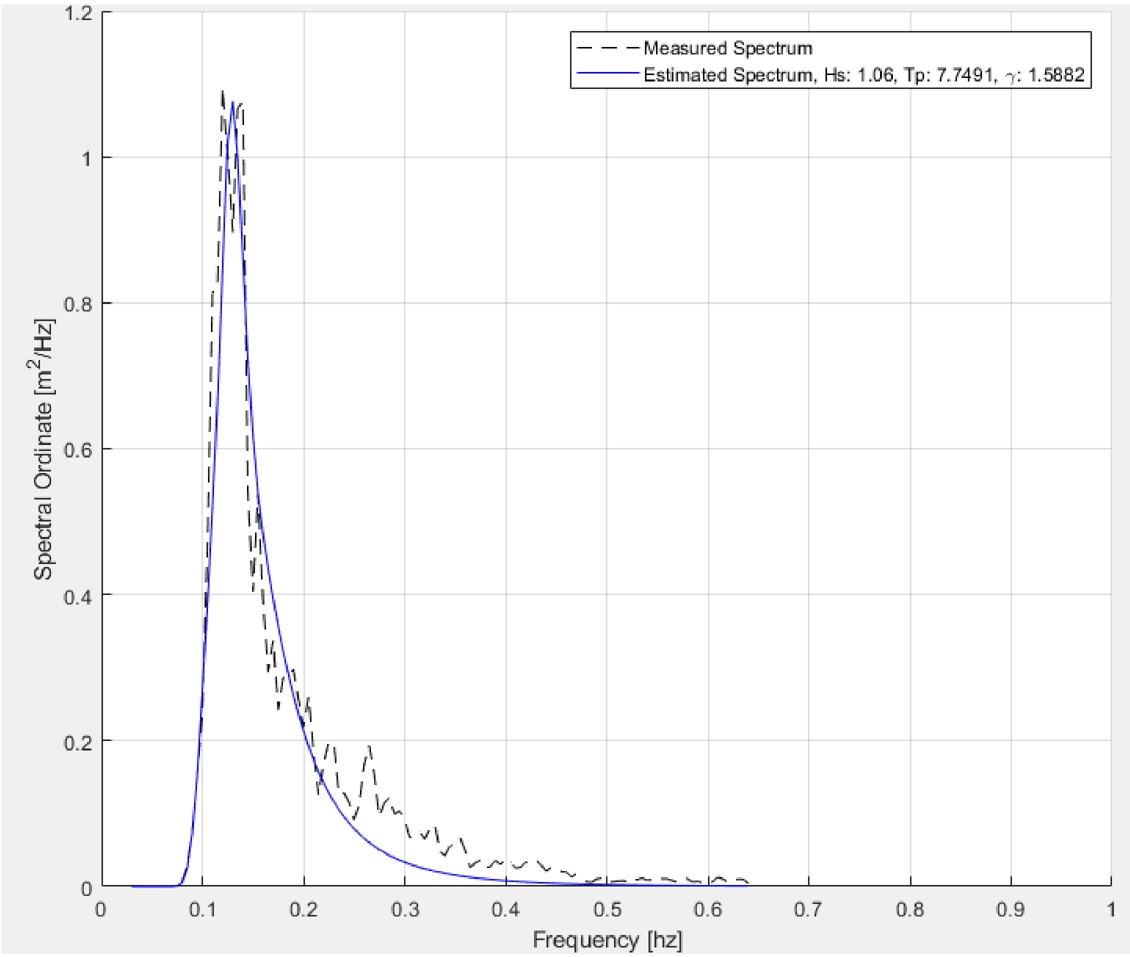


FIGURE. 17-1 FITTED JONSWAP SPECTRUM

Spreading Fitting

The spreading of energy from the mean wave direction can be described using a spreading function, where the most commonly used is the “cos2s” function [Ref.1]:

$$D(\theta) = \begin{cases} C(s)\cos^{2s}(0.5(\theta-\bar{\theta})), & for\ |\theta-\bar{\theta}| < \pi/2 \\ 0 & otherwise \end{cases} \quad (7)$$

Where:

$$C(s) = \frac{\Gamma(s+1)}{2\sqrt{\pi}\Gamma(s+0.5)} \quad (8)$$

And Γ is the Error function, $\bar{\theta}$ is the mean wave direction, and “s” is the spreading coefficient. The only unknown variable is the spreading coefficient “s”, which has been estimated using equation 6, this time “s” being the parameter to be fitted. The spreading coefficient must be an integer to avoid complex value energies. Note that for a spread spectrum the spectral ordinate is calculated by:

$$S(\omega,\theta) = D(\theta)S_j(\omega)$$

Below is an example of spectra with idealized spreading and deterministic spreading.

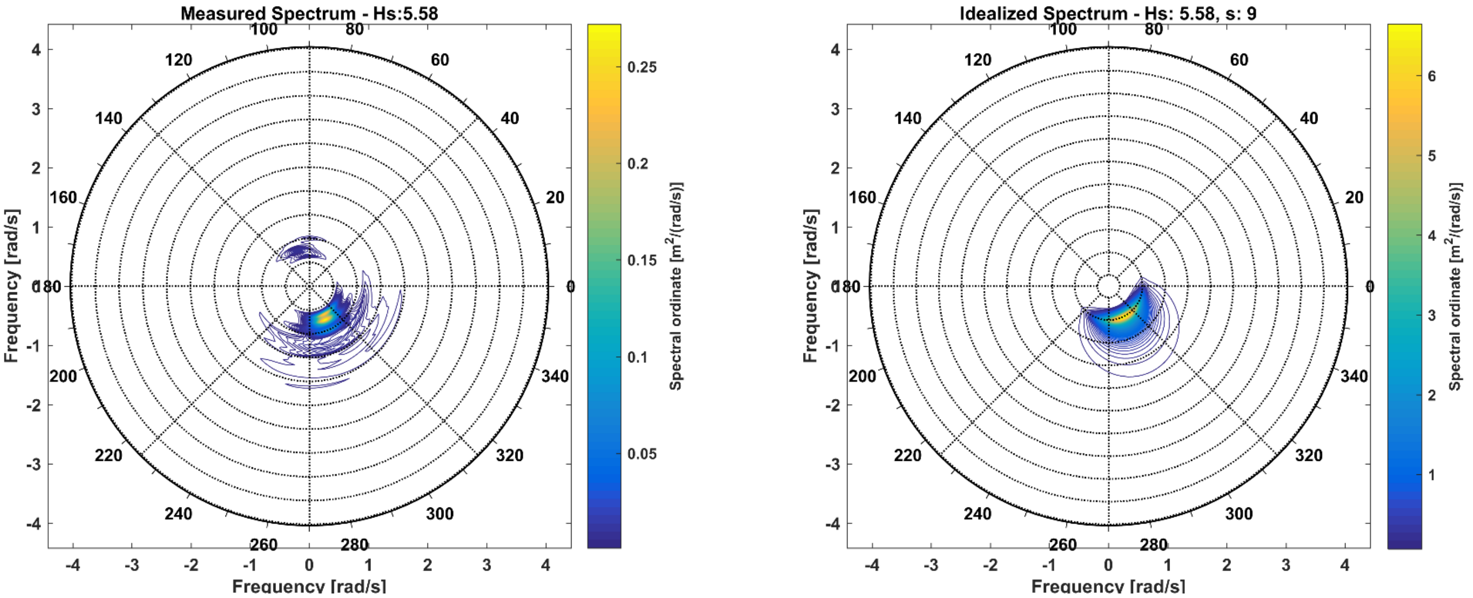


FIGURE. 17-2 FITTED SPREADING COEFFICIENT: S=9, ENV103P1

References

1. Ocean Engineering, "Sea State Characterisation for Wave Energy Performance Assessment at the Biscay Marine Energy Platform" P. Ricci, O. Duperray, Y. Torre-Enciso, O. Liria, and J.L Villate, (2007)

18. ANNEX XI: WORKSCOPE POTENTIAL

A potential work-scope for mooring analysis (and design) is outlined in the following, based on a recent study for a structure with mooring, water-depth and environment of similar proportions to the Oceantec-Idom's WEC. **This is not a template for what has to be done, but may act as a useful discussion point.**

Limit state analysis

The design of the mooring system would be based upon analyses that include Ultimate (intact), Accidental (line/component failure), Fatigue limit states.

1) Severe Storm Survival - Ultimate Limit State (ULS)
   (a) Mooring Line Tensions
   b) Anchor Tensions
   c) Anchor Uplift
   d) Buoy Connection Loads

2) Line Failure - Accidental Limit State (ALS)
   a) Mooring Line Tensions
   b) Anchor Tensions
   c) Anchor Uplift
   d) Buoy Connection Loads

3) Fatigue Life - Fatigue Limit State (FLS) (Specified Required Design Life in years)

The analyses may be based on dynamic time domain, for a 3-hour simulation. Various environment directions might be tested e.g. every 22.5deg. For the mooring assessment in the damaged condition, each mooring in turn would be broken. The damage condition analyses may also be 3-hour time domain.

Acceptance criteria

The acceptance criteria followed those of well-established mooring codes, and included Factor of Safety in Intact, Single Line Failure, load at drag anchor, uplift limitations, and fatigue.

Fatigue assessment

The fatigue analyses might be based on one 3-hour simulation for each Hs-Tz combination in the scatter table.

Direction of the environments should be considered.

Sensitivity studies on wave & current relative directions, and current velocity might be done using the seastate that gave rise to the most onerous fatigue damage condition.

The fatigue damage could be assessed for each of the mooring components and links, throughout the mooring line length.

T-N curves might be applied for standard components, and S-N curves might be applied for non-standard components.

Stress concentration factor evaluation and corrosion

For special non-standard links (tri-plates, etc) components, finite element models and analyses might be done to evaluate the Stress Concentration Factor, for application in the fatigue analysis.

Corrosion levels may also be taken into consideration in the evaluation of the fatigue damage.

Modelling features

The pennant and buoys could be explicitly modelled as lines with spar buoys.