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Task 6: Supporting Studies

Evaluation of WETS Mooring: Failure Mode Investigation Report

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EVALUATION OF WETS MOORING

Failure Mode Investigation Report

Sea Engineering

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3	12/09/2017	Improvement to Berth B results	OZR/AA	TV	JG

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1 INTRODUCTION

Following the failure of the vacant WETS berth B (80m WD) mooring system and damage to the WETS berth A (60m WD) mooring system with the Fred Olsen Lifesaver wave energy converter (WEC) connected, Noble Denton Consultants trading as DNV GL has been requested by Sea Engineering Inc. to perform a mooring integrity review of the WETS mooring systems, berth sites A and B.

The overall scope of work is to evaluate the current design and provide recommendations on high level modifications to hardware components. This is delivered through:

- DNV GL technical note "Mooring integrity review", doc. No. L32172 Rev 1 (see Appendix E)
- Failure mode investigation and high-level mooring loads analysis provided in the main text of this report.

Re-design of the mooring system configuration (including resizing of any components) is outside the scope of this design review.

The extent of the scope of work for each deliverable is given in section 2.1.

1.1 Abbreviations

ALS	Accidental limit state
FLS	Fatigue limit state
MBL	Minimum break load
RP	Return period
TDP	Touchdown point
WEC	Wave energy converter
WETS	Wave energy test site
WD	Water depth
ULS	Ultimate limit state

2 METHODOLOGY

2.1 Scope of work

The overall scope of work includes failure mode investigation making use of OrcaFlex models of both berth A and berth B mooring systems. The outcomes of the mooring integrity review (see Appendix E) and the high-level mooring loads analysis are used to evaluate the existing design and provide recommendations on high level modifications to hardware components.

The extent of the scope of work provided in the mooring integrity review (see Appendix E) is:

- Review metocean conditions, mooring analysis report and associated documents of the mooring system design against industry requirements (e.g. design load cases, safety factors, allowance for marine growth, corrosion, etc.). Review includes the existing analyses reports (provided by the Customer) covering occupied and vacant states of both mooring sites.
- Mooring integrity review of manufacturing (component) and installation records and inspection report. Identification of potential failure modes with the WETS mooring systems (berth sites A and B) and observations of anomalies as well as areas for further inspection (if required).
- Evaluation of the hardware selection for the existing mooring configurations with regards to appropriateness for use in offshore mooring environment and identification of long term integrity risks. Recommendations are provided for high-level design modifications and operational advice.

This report advances the failure mode investigation from the mooring integrity review (see Appendix E) through development of OrcaFlex models of the berth B mooring system with no WEC connected and the berth A mooring system with the Lifesaver WEC connected. The numerical model of the Lifesaver WEC is simplified considering only total excursion force and simplified wave frequency motion parameters.

The OrcaFlex models are used to assist in understanding the behaviour of the mooring lines and appendages. The following set of analyses are conducted based on the outcomes of the initial integrity review:

- ULS cases to check against standard DNVGL-OS-E301, and compare (as much as possible given the limited information) to previous analysis carried out by design Contractor.
- Check physical behaviour and compare against predicted failure modes from Appendix E; e.g. sinkers motion, anchor uplift, slack line.
- Lifesaver WEC offset with sinkers, lost sinkers (no. 4 & 5), no sinkers so Customer can evaluate hazard posed to power cable.
- Sensitivity studies – anchor position, wave period, simulation realizations.
- High level modifications – no sinkers, use of heavier chain.

It is noted that the analyses performed in this report are preliminary and high-level, so are not suitable for design. Further analysis work is required to confirm the recommendations provided in this report for design.

2.2 General system description

2.2.1 Base case model

Two separate models of Berth A (with Lifesaver WEC connected) and Berth B (vacant) are created using OrcaFlex. The following effects are included:

- The "base case" analysis for berth A includes the Lifesaver WEC connected to the mooring system according to as-designed conditions. A representation of the berth A base case OrcaFlex model is shown in Figure 2-1.
- The "base case" analysis for berth B includes only mooring line 1 of the as-designed mooring system, with the surface buoy attached. The purpose of this report is to assist in understanding the behaviour of the mooring lines and appendages, therefore a single line model is considered to be representative of all three lines. Berth B OrcaFlex model is shown in Figure 3-2.
- The WEC model includes mass and inertia, added mass and radiation damping, second order drift loads, simplified wave frequency response parameters, current and wind loading. See section 3.9 for model description.
- The mooring lines are modelled according to the as-designed conditions, ref. /1/ and /2/. All line dynamics effects are accounted for in the OrcaFlex model including, stiffness, mass, added mass, drag load, seabed friction and physical effect of the appendages (sinkers, tow plate etc.).
- The surface buoys are modelled using a simplified 3D buoy including mass and buoyancy. Wave and current loading is applied based on a Morison model.
- The mooring dynamic analysis is fully coupled and performed in time domain. The simulation length is 3-hours according to DNVGL-OS-E301, ref. /11/. A single realization of the seastate is considered. DNVGL-OS-E301, ref. /11/ requires that multiple realisations (seeds) of duration 3 hours are simulated to establish an extreme value distribution and derive the most probable maximum. This is outside the scope of work, a sensitivity study on the seed is performed.

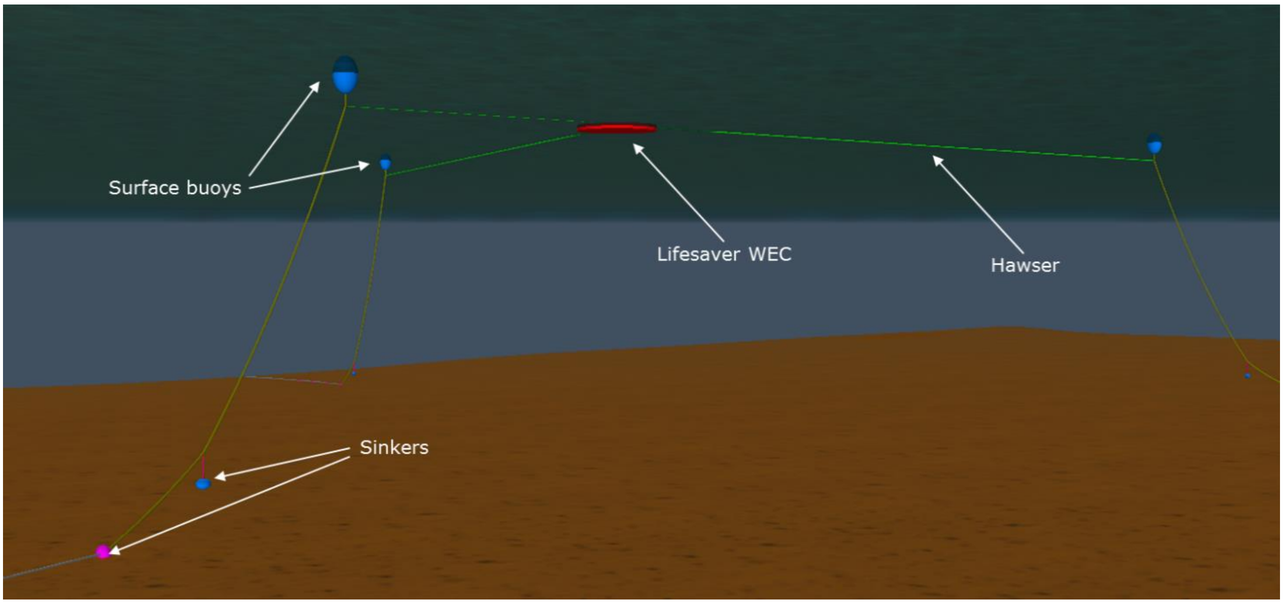

Figure 2-1 Berth A mooring system

2.2.2 Sensitivity studies

A number of sensitivity studies are performed for berth A to assist in understanding the behaviour of the mooring lines and appendages, and evaluate high-level design component modifications:

- Berth A base case and wave period variation
- Berth A base case and seed variation
- Berth A with anchor position variation ±10m (based on deviation seen between as-designed and as-installed anchor positions, see Appendix E)
- Berth A with lost sinkers no. 4 & 5
- Berth A with no sinkers
- Berth A with sinkers 4 and 5 replaced by heavier chain.

2.3 Criteria of acceptance

2.3.1 Survival conditions

DNVGL-OS-E301, ref. /11/, requires the survival condition to be assessed for the 100-year return period (RP) extreme seastates. Mooring strength (intact and line redundancy), fatigue and maximum floater offset should be evaluated. In this report, only the intact mooring strength is assessed (ULS case). The limits for the Lifesaver WEC offset with regards to the allowable excursion of the power cable are not provided by the Customer. Accidental limit states (ALS) and fatigue limit states (FLS) are not evaluated as this is outside the scope of work. The mooring system limiting capacities and ultimate limit state (ULS) safety factors for mooring tension are given in Table 2-1 and Table 2-2 below.

Table 2-1 Limiting capacities

Chain MBL (t)	Anchor capacity (t)	Anchor allowable uplift (t)	Pigtail MBL (t)
375.9 (un-corroded) 336.8 (corroded)	204.2	0.0	262.9 (un-corroded) 235.9 (corroded)

Notes Corrosion is conservatively assumed as 0.8mm/year, ref. /12/, and the design life is taken as 5 years
Minimum break load (MBL) is based on ABS Rules for testing and certification of materials, ref. /13/
The anchor capacity is based on Appendix E.

Table 2-2 ULS safety factors

Maximum tension	Anchor tension
2.1	1.5

Notes The safety factor for maximum tension is conservative, DNVGL-OS-E301 requires the use of partial safety factors and as such 2.1 should only be applied to the dynamic tension (maximum – mean) and 1.4 should be applied to the mean.

2.3.2 Operating conditions

The operability of this mooring system is assessed by evaluating sinker motion in operating seastates (this should be minimal to reduce wear) and the likelihood of mooring line snatching which can be indicated by zero tension in the mooring line (i.e. line going slack). Line snatching can also increase the effects of wear between chain links and components.

3 MODEL DESCRIPTION

3.1 Reference system

The model global reference system is such that the X axis is towards East and the Y axis is towards North. The centre of the model global axes are shown below.

Table 3-1 Centre of model global axes

Berth	Easting (m)	Northing (m)
A	-629,113.99	2,375,148.01
B	-628,331.70	2,375,633.80

3.2 Seabed

The seabed is modelled in OrcaFlex as a 3D profile described in ref. /1/. The water depth at the mooring centre is approximately 60m for berth A and 80m for berth B. OrcaFlex model plots showing the seabed profile are shown in Figure 3-1 and Figure 3-2 below.

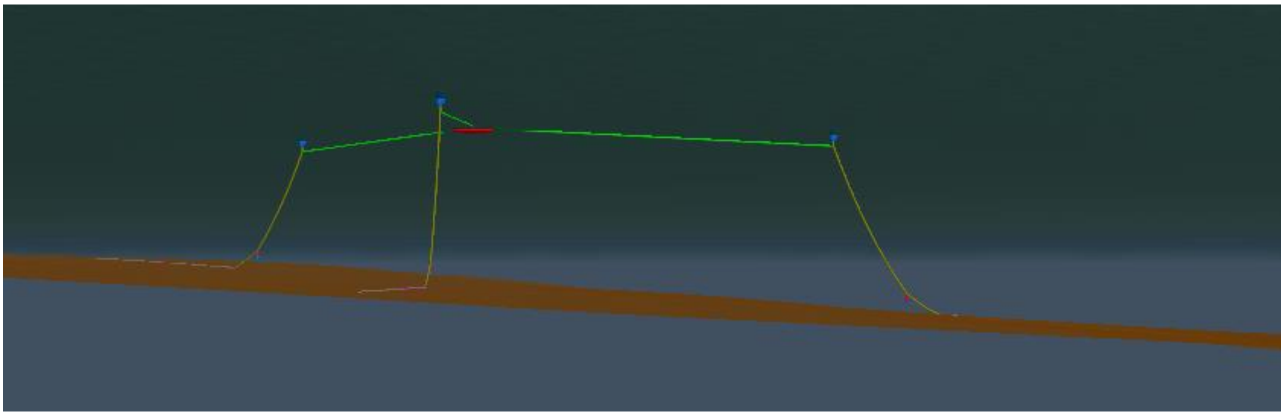

Figure 3-1 Site A (looking West)

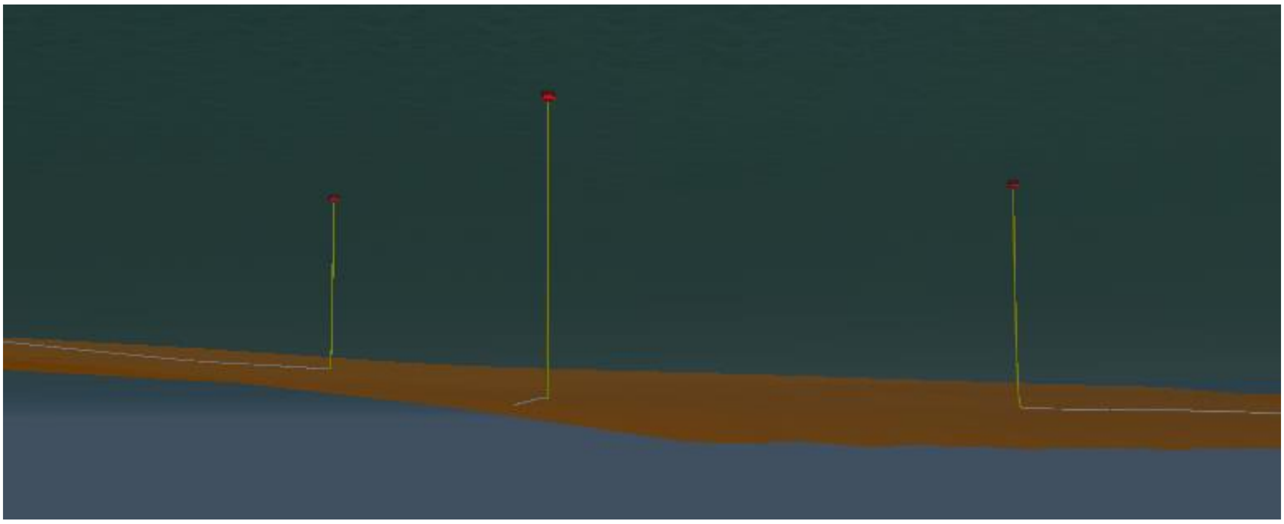

Figure 3-2 Site B (looking West)

3.3 Metocean conditions

3.3.1 Wave data

A Pierson Moskowitz spectrum is used throughout the analysis, which is assumed based on ref. /2/, in which it is shown that the maximum nylon mooring hawser tension is higher for a broad spectral shape (JONSWAP gamma = 1) than for a narrower spectrum (gamma = 3.3).

The scatter diagram provided in ref. /4/ is used to define the operating conditions. A range of Hs-Tp values is selected so that the most probable wave conditions are considered.

The survival conditions (for which the WEC cannot operate but which the system is designed to sustain) are based on ref. /1/. Survival and operating conditions are shown in Table 3-2.

Table 3-2 Hs-Tp operating and survival conditions

Seastate	Hs (m)	Tp (s) Case 1	Tp (s) Case 2
Operating	1.5	5.5	7.5
	4.5	12.5	14.0
Survival – 100-year RP	6.5	14.4	N/A

3.3.2 Wind data

The 100-year RP 10-minute average wind speed is 26.1m/s as per ref. /1/. Based on DNV-RP-C205, ref. /15/, this corresponds to 28.9m/s 1-minute average wind speed which is applied in the mooring load analysis as a constant. With lack of data for the most probable wind speed in operating conditions, the 100-year wind speed is conservatively applied for operating and survival conditions.

3.3.3 Current data

The 100-year RP current speed profile, based on ref. /6/ is shown below. For consistency between wind and current, the 100-year current speed is conservatively applied for operating and survival conditions.

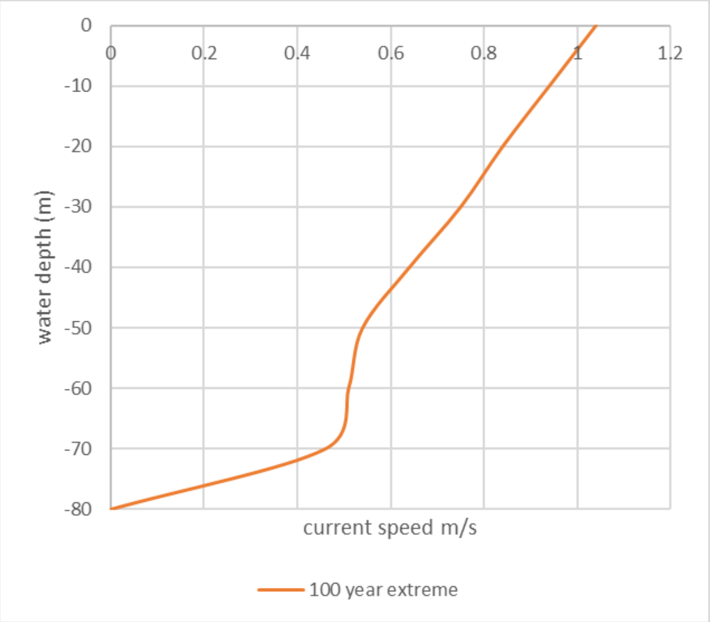

Figure 3-3 Current profile

3.4 Anchors

The anchor coordinates, extracted from ref. /1/, are copied below.

Table 3-3 Anchor coordinates

Anchor	Design West (m)	Design X (m)	Design North (m)	Design Y (m)
A1	629434.00	320.01	2375147.96	-0.05
A2	629058.00	-55.99	2375463.00	314.99
A3	628952.85	-161.14	2374956.39	-191.62
B1	628731.70	400.00	2375633.80	0.00
B2	628262.31	-69.39	2376027.69	393.89
B3	628074.59	-257.11	2375327.40	-306.40

3.5 Mooring main chain

The mooring chains used for the three lines are ABS marine grade 3 and have diameter of 2.75 inches. The characteristics are presented below. Based on the inspection report ref. /8/, little marine growth is observed on the dynamic portion of the catenary. This study is concerned with the dynamic behaviour of the mooring line; as such the model does not include marine growth. More detailed mooring analysis for design should include the effect of marine growth, guidance is given in DNVGL-OS-E301, ref. /11/.

Table 3-4 Chain properties

Item	Main chain
Grade	ABS marine grade 3
Link	Studlink
D (mm)	70.0
Mass in air (t/m)	0.107
Mass in water (t/m)	0.093
EA (kN)	494,900
Drag coefficient normal (ref. /11/)	2.6
Drag coefficient axial (ref. /11/)	1.4
Added mass coefficient (ref. /11/)	1.0
Friction coefficient (ref. /14/)	1.0

3.6 Sinkers

On each of the lines (for both berths) five sinkers are attached to each mooring line based on the mooring make-up given in ref. /2/. The location of the sinkers along the lines is shown in Table 3-5. Based on ref. /1/ the sinkers have a mass of 4.1t and a volume of 1.7m^3.

Table 3-5 Sinkers location on lines

Sinker No.	Berth A. Distance from anchor (m)			Berth B. Distance from anchor (m)		
	A-1	A-2	A-3	B-1	B-2	B-3
5	159	149	123	215	216	235
4	141	133	106	187	190	210
3	123	117	89	159	162	179
2	105	101	72	130	133	152
1	87	85	55	102	105	122

Notes Berth B mooring lines B-2 and B-3 sinker locations are provided for information only. Analysis performed for line 1 only.

The sinkers are connected to the lines with a chain pigtail (pennants). As the chain tension varies the catenary profile of the line is modified and the sinkers -and pennant- may or may not rest on the seabed. This behaviour brings instability to the numerical model. To solve this issue sinkers 1 to 4 are modelled as clump weights attached to the main chain without modelling the pigtails. Sinker no. 5 (furthest away from the anchor) is modelled in full as a 3D buoy attached to the main line using a pigtail since it is always suspended in the water column. This model simplification for sinkers 1 to 4 is considered to have negligible effect on the line dynamic response.

3.7 Surface buoys

The dimensional properties of the surface buoys MB-340 are obtained from the following data sheet extract shown below (from marine fenders international).

DECK **SHIPSERV** Onboard SS16-0154

MARINE FENDERS INTERNATIONAL

OCEAN GUARD MOORING BUOYS

CONSTRUCTION FEATURES:
- Central steel strength member
- Heat-laminated, impact-absorbing, closed-cell, rigid urethane flotation foam
- Abrasion-resistant, filament nylon-reinforced urethane elastomer skin
- Internal radar reflectors
- Non-marking
- Puncture resistant
- Unsinkable
- Corrosion resistant

END-FITTING OPTIONS:
- Mooring Tee
- Quick Release Hook
- Hawser Pipe

MOORING BUOYS

BUOY MODEL	BUOYANCY NET		BUOY WEIGHT		DIAMETER OVERALL		HEIGHT BUOY BODY		HEIGHT OVERALL		WORKING LOAD	
	LBS	KG	LBS	KG	FT	M	FT	M	FT	M	LBS	TONS
MB-25	5,512	2,500	1,756	797	6.1	1.9	3.6	1.1	7.6	2.3	100,000	45
MB-35	7,716	3,500	2,340	1,061	7.0	2.1	4.3	1.3	8.5	2.6	150,000	68
MB-50	11,023	5,000	2,371	1,075	7.5	2.3	4.9	1.5	8.6	2.6	150,000	68
MB-70	15,432	7,000	2,938	1,333	8.5	2.6	5.0	1.5	8.6	2.6	200,000	91
MB-90	19,842	9,000	4,657	2,112	10	3.0	5	1.5	8.6	2.6	200,000	91
MB-115	25,353	11,500	5,109	2,317	10	3.0	6.1	1.9	9.5	2.9	200,000	91
MB-135	29,762	13,500	6,017	2,729	10.5	3.2	6.5	2.0	10.0	3.0	300,000	136
MB-160	35,274	16,000	6,333	2,873	11	3.4	6.8	2.1	11.75	3.6	300,000	136
MB-185	40,785	18,500	6,836	3,101	11.1	3.4	7.8	2.4	12.7	3.9	300,000	136
MB-225	49,604	22,500	8,491	3,852	12.0	3.7	8.1	2.5	12.9	3.9	300,000	136
MB-250	55,116	25,000	9,469	4,295	12.5	3.8	8.3	2.5	13.1	4.0	300,000	136
MB-275	60,627	27,500	9,965	4,520	12.6	3.8	8.9	2.7	13.7	4.2	300,000	136
MB-340	74,957	34,000	11,841	5,371	13.83	4.2	9	2.7	13.8	4.2	300,000	136
MB-455	100,310	45,500	14,599	6,622	15	4.6	10	3.0	14.8	4.5	300,000	136

Actual values for above sizes may vary +/- 15% due to variations in materials, temperatures and tolerances.

3.8 Hawsers – Berth A

The pennants connecting the mooring chain to the WEC consist of three sections: 12.5m of Dyneema rope, 130m (for line 1 and 2) or 126m (for line 3) nylon hawser and 3m of chain. The stiffness of the complete pennant is taken as the stiffness of the nylon component, since the nylon stiffness is significantly lower than that of the other components and so governs the load extension curve. The stiffness of the line is modelled as non-linear, the curve used corresponds to the broken-in properties provided in ref. /16/ for the relevant lengths and for MBL 50t.

The lines are given a pretension of 1t or 4t to assess the effect on the results

3.9 Lifesaver WEC

To compute the Lifesaver WEC's hydrodynamic parameters required for the OrcaFlex mooring load analysis a diffraction/radiation analysis is performed using the hydrodynamic package AQWA. The Lifesaver WEC is modelled based on ref. /7/. A representation of this model is shown in Figure 3-4 and the model particulars are given in Table 3-6.

In the OrcaFlex model of Berth A, the PTO system, comprising the subsea buoys, risers and chain baskets, is not modelled. This is conservative from the perspective of survivability of the mooring system, since the PTO system will restrict the WEC motions and add damping.

Current drag load and wind drag loads are included in the WEC OrcaFlex model. The current and wind coefficients are copied in Figure 3-5 and Figure 3-6.

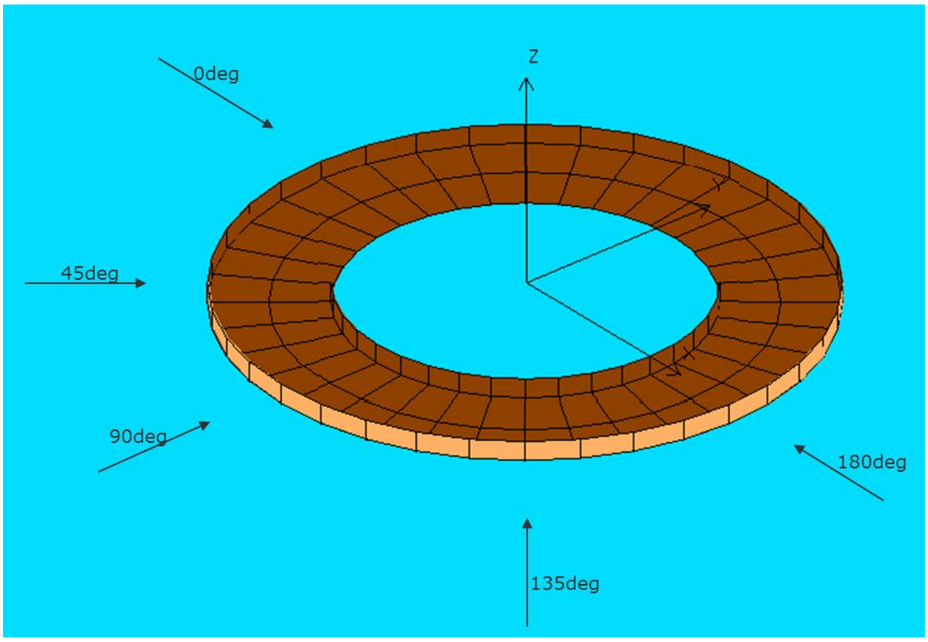

Figure 3-4 AQWA LINE model plot of Lifesaver WEC

Table 3-6 Lifesaver WEC mass particulars

Item	Units	Value
Mass	t	70.5
Diameter internal	m	9.8
Diameter external	m	16.0
Moment of inertia Ixx	tm^2	6210
Moment of inertia Iyy	tm^2	6210
Moment of inertia Izz	tm^2	12400

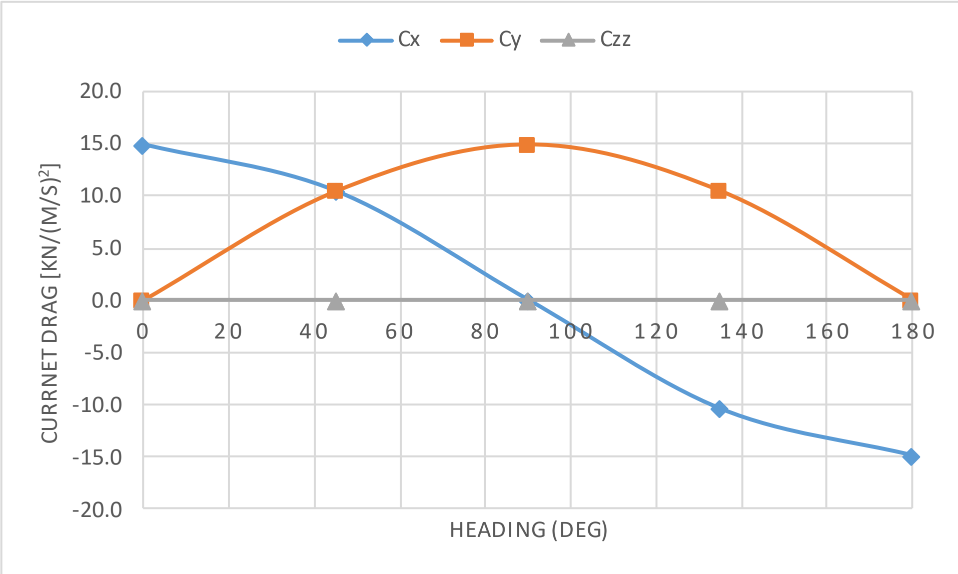

Figure 3-5 **WEC current load coefficients**

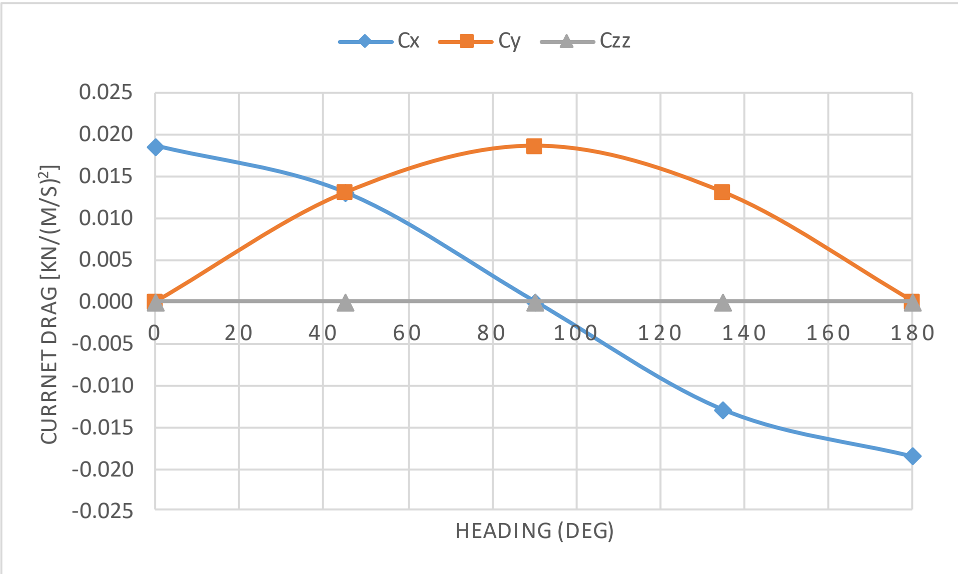

Figure 3-6 **WEC wind load coefficients**

4 RESULTS

4.1 Berth A base case

The key results for Berth A operating and survival conditions for the base case are summarised in Table 4-1. The full set of results are presented in Appendix A. These are preliminary results based on a single realization of the seastates considered and a more rigorous analysis is required for design.

The offset is measured at the centre of the WEC from the mooring system centre. Note that in this analysis the PTO system is not modelled since the focus is on assisting in understanding the behaviour of the mooring lines and appendages, therefore the restraining effect of the chain basket legs is missed. Based on this, the offsets quoted here are not representative of the WEC arrangement.

These results show that the mooring line is sufficiently strong to withstand the extreme loads in survival conditions and the anchor holding capacity meets the requirement. Corrosion allowance should be considered as required by the design code; in this case the MBL far exceeds the maximum tension and so this is not a limiting factor.

For the seastate analysed with Hs 1.5m, it is observed that the mooring chain experiences slack line effects and sinkers 4 and 5 experience significant motion. It can be therefore inferred that for seastates greater than Hs 1.5m these effects will remain. From the scatter diagram provided in ref. /4/ this corresponds to 74% exceedence (i.e. for 74% of the time the mooring system will experience these effects). This confirms the failure modes prediction of wear between mooring components, sinkers and chain links and strength issues due to snatch load, low bend radii of chain links and security of pins.

Table 4-1 Summary of results Berth A base case

Condition	Item	Base case 5 sinkers	Limit	Units	Factor of safety
Survival	Maximum tension chain[1]	55.6	336.8	t	6.0
Hs 6.5m	Maximum anchor tension	44.4	204.2	t	4.6
	Maximum uplift	0.0	0.0	t	N/A
	Maximum tension pigtail[2]	63.2	235.9	t	3.7
	Maximum WEC offset[3]	44.9	N/A	m	N/A
Operating	Minimum tension chain	<0.0	>0.0	t	N/A
Hs 1.5m	Motion of sinker 5	~6.0	<1.0	m	N/A

1 It is seen that the maximum tension occurs at the tow plate that connects the main chain to the hawser

2 Sanity checks are performed modelling sinker 5 as a clump weight attached directly to the main chain, see section 3.6. In this case the acceleration of sinker 5 is found to be significantly less than when modelling the sinker-pigtail arrangement, which would lead to lower tension in the chain pennant than indicated in this table. Future analysis should investigate further the challenge of modelling the sinker-pigtail arrangement.

4.2 Berth A lost sinkers

Analysis is performed to evaluate the effect of losing sinkers 4 and 5 as per the inspection report, ref. /8/ and study the need for sinkers through modelling the mooring system without sinkers. The key results are summarised in Table 4-2. The full set of results are presented in Appendix B and Appendix C for the 3 sinkers and no sinker cases, respectively.

The effect of losing sinkers 4 and 5 is an increase in the WEC offset and a small increase in tension. The case analysed removing all sinkers shows small uplift force at the anchor; this is also illustrated by the minimum distance between the touchdown point (TDP) and the anchor being equal to zero. DNVGL-OS-

E301, ref. /11/, requires that for anchors not designed to take uplift forces, the mooring lines shall have enough length to avoid uplift at anchors for all relevant design conditions in the ULS.

Table 4-2 Summary of results Berth A lost sinkers

Condition	Item	Base case 5 sinkers	Base case 3 sinkers	Base case no sinkers	Units
Survival	Maximum tension chain	55.6	56.5	56.2	t
Hs 6.5m	Maximum anchor tension	44.4	48.7	51.6	t
	Maximum uplift	0.0	0.0	1.0	t
	Maximum WEC offset	44.9	49.6	52.9	m
Operating	Minimum tension chain	<0.0	<0.0	<0.0	t

4.3 Berth A sensitivity studies

4.3.1 Replacement of sinker 4 and 5 by heavier chain section

This set of runs is performed to assess the proposal by the Customer, to replace a section of the main chain (ABS marine grade 3 link diameter 70mm) by ABS grade 3 chain with 89mm link diameter. This is over a section of 27m around the position of sinker 5 (in the thrash zone) with the intention of replacing the mass of the lost sinkers 4 and 5.

Results for a critical case in survival conditions show that the minimum clearance of sinker 1 is reduced by approximately 1m when compared to the results for 3 sinkers only (see Appendix B). Adding 27m of heavier chain to the 3-sinkers configuration is not sufficient to replace the catenary of sinkers 4 and 5. This is explained by the fact that the additional submerged mass of replacing 27m of main chain with 27m of heavier chain line is 1.6t. By comparison, the combined submerged weight of the two sinkers plus pigtails is 5.2t.

4.3.2 Seed variation

The results presented in this report are the maximum values obtained for a single seed, i.e. for a single wave component phasing of the wave spectrum. To assess the effect of the seed variation on the results a set of ten runs of the same file but with different seeds is performed for survival condition at Berth A, for the 5 sinkers base case with 1t hawser pretension.

The extreme value may be taken as the mean of the maxima of the extreme value distribution of the individual maximum from the ten realizations.

The results obtained for the line tension are summarised below. They show that there is significant variance in the maximum tension due to statistical variability, and so it is required to consider multiple seeds for design.

Table 4-3 Effect of multiple seeds on line tension

	Max of max (t)	Min of max (t)	Mean of max
line 1	68.0	34.3	43.5
line 2	46.8	34.8	40.7
line 3	58.7	36.4	49.0
Extreme	68.0	34.3	40.7

4.3.3 Wave period

The effect of varying peak wave period, Tp, is observed in the base case results as a Tp range extracted from the available scatter tables is used to perform the analyses.

Shorter wave periods lead to greater mooring tensions, therefore the 100-year IFORM contour should be considered for the mooring analysis. This observation is confirmed by further runs for the base case survival cases where Tp is reduced from 14.4s to 8.0s in increments of 2.0s.

4.3.4 Anchor position

The effect of anchor positioning inaccuracy is investigated based on the deviation seen between the as-designed and as-installed anchor positions, see Appendix E. For the 5 sinkers base case the anchor position for line A-1 is changed by 10m further and nearer to the mooring centre. The line lengths are not modified but the hawser lengths are adjusted so the Lifesaver WEC remains at the mooring centre in static equilibrium, and the same range of pretension is maintained.

The results obtained in these conditions show insignificant variation from the base case results.

4.4 Berth B base case

The behaviour of mooring system on Berth B site is studied by analysing line B-1 only. Mooring line B-1 is selected since it is more aligned to the predominant weather, hence will see the greatest tension, and the anchor is at an intermediary water depth compared to lines 2 and 3.

The full set of results are presented in Appendix D for the 5 sinkers, 3 sinkers and no sinker cases. Like for Berth A with the WEC connected, the mooring line is sufficiently strong to withstand the extreme loads in survival conditions and the anchor holding capacity meets the requirement. For the seastate analysed with Hs 1.5m, it is observed that the mooring chain experiences slack line effects and sinker no. 5 of each mooring line experiences significant motion.

5 CONLCUSIONS

This report has advanced the failure mode investigation from the mooring integrity review (see Appendix E) through development of OrcaFlex models of the berth B mooring system with no WEC and the berth A mooring system with the Lifesaver WEC connected.

It is noted that the analyses performed in this report are preliminary and high-level, so are not suitable for design. Further analysis work is required to confirm the recommendations provided in this report for design.

The following failure modes and long term integrity risk areas for WETS mooring systems berth sites A and B are confirmed from the analyses performed:

Component selection

- Wear - excessive wear between mooring components, sinkers and chain links.
- Wear - hawser can get damaged, and easily kinked and bent.
- Strength - issues due to snatch load, low bend radii of chain links and security of pins.
- Erosion and trenching of seabed due to excessive motion of thrash zone.
- Fatigue - mooring system is highly dynamic, fatigue should be assessed.
- Fatigue - equipment not suitable for offshore mooring.

Input data/analysis

- There is significant variance in the maximum tension due to statistical variability, it is required to consider multiple seeds for design.
- Shorter wave periods lead to greater mooring tensions, therefore the 100-year IFORM contour should be considered for the mooring analysis.
- Additional mass to the main chain is required to ensure there is no uplift at the anchor. In the existing design this is added through the use of sinkers, however these have wear issues.

6 REFERENCES

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Appendix A Results for Berth A – 5 sinkers

Hawsers pretension (t)	Environment heading (deg)	Hs (m)	Tp (s)	Wind Speed (m/s)	Current Speed (m/s)	WEC offset (m)	A-1 Chain Force at anchor Max (t)	A-1 Chain uplift at anchor Max (t)	A-2 Chain Force at anchor Max (t)	A-2 Chain uplift at anchor Max (t)	A-3 Chain Force at anchor Max (t)	A-3 Chain uplift at anchor Max (t)	A-1 pigtail tension Max (t)	A-2 pigtail tension Max (t)	A-3 pigtail tension Max (t)	A-1 sinker5 Z range (m)	A-1 sinker4 clearance (m)	A-1 sinker3 clearance (m)	A-1 sinker2 clearance (m)	A-1 sinker1 clearance (m)	A-2 sinker5 Z range (m)	A-2 sinker4 clearance (m)	A-2 sinker3 clearance (m)	A-2 sinker2 clearance (m)	A-2 sinker1 clearance (m)	A-3 sinker5 Z range (m)	A-3 sinker4 clearance (m)	A-3 sinker3 clearance (m)	A-3 sinker2 clearance (m)	A-3 sinker1 clearance (m)	A-1 Chain TDP min position from anchor (m)	A-2 Chain TDP min position from anchor (m)	A-3 Chain TDP min position from anchor (m)
1	180	1.5	5.5	28.9	1.04	19.6	18.2	0.0	7.4	0.0	11.8	0.0	4.9	4.3	5.2	6.2	8.2	2.2	0.0	0.0	1.4	3.1	0.0	0.0	0.0	3.8	13.6	0.0	0.0	0.0	106.0	122.0	91.0
1	230	1.5	5.5	28.9	1.04	18.0	12.0	0.0	11.5	0.0	10.3	0.0	4.7	4.5	6.8	4.8	4.5	0.0	0.0	0.0	4.8	5.6	0.4	0.0	0.0	3.9	2.0	0.0	0.0	0.0	123.0	108.0	99.0
1	180	1.5	7.5	28.9	1.04	15.5	10.7	0.0	6.9	0.0	10.2	0.0	4.9	3.9	4.3	5.6	6.3	0.8	0.0	0.0	2.9	0.4	0.0	0.0	0.0	2.0	3.0	0.0	0.0	0.0	111.0	127.0	94.0
1	230	1.5	7.5	28.9	1.04	10.4	10.4	0.0	1.0	0.0	10.4	0.0	4.3	4.2	5.0	4.9	4.3	0.0	0.0	0.0	4.4	5.8	0.3	0.0	0.0	1.7	3.1	0.0	0.0	0.0	123.0	111.0	91.0
1	180	4.5	12.5	28.9	1.04	34.2	35.2	0.0	7.2	0.0	10.2	0.0	5.6	5.1	4.8	12.9	13.7	7.7	0.0	0.0	4.7	3.9	0.0	0.0	0.0	11.3	16.8	0.4	0.0	0.0	70.0	118.0	86.0
1	230	4.5	12.5	28.9	1.04	35.5	19.2	0.0	21.5	0.0	11.1	0.0	6.7	6.8	30.5	13.2	9.1	2.8	0.0	0.0	11.9	9.7	3.6	0.2	0.0	9.1	2.4	0.0	0.0	0.0	105.0	94.0	101.0
1	180	4.5	14.0	28.9	1.04	26.5	23.2	0.0	6.3	0.0	9.1	0.0	5.5	4.6	4.2	11.5	10.5	4.2	0.6	0.0	8.3	2.0	0.0	0.0	0.0	8.3	5.9	0.3	0.0	0.0	93.0	120.0	86.0
1	230	4.5	14.0	28.9	1.04	24.5	12.9	0.0	13.4	0.0	9.1	0.0	5.4	5.1	8.6	9.6	6.1	0.6	0.0	0.0	10.1	8.2	2.3	0.0	0.0	6.1	3.3	0.0	0.0	0.0	112.0	102.0	95.0
1	180	6.5	14.4	28.9	1.04	39.9	44.4	0.0	8.1	0.0	9.1	0.0	7.1	7.1	5.2	15.5	15.7	9.9	0.0	0.0	6.6	5.2	0.0	0.0	0.0	13.2	17.6	1.0	0.0	0.0	45.0	118.0	84.0
1	230	6.5	14.4	28.9	1.04	44.9	26.1	0.0	23.8	0.0	11.2	0.0	6.7	7.0	63.2	16.6	12.0	5.9	1.7	0.0	14.7	12.1	6.2	2.0	0.0	11.1	2.3	0.0	0.0	0.0	88.0	85.0	101.0
MAX operational						35.5	35.2	0.0	21.5	0.0	11.8	0.0	6.7	6.8	30.5	13.2	13.7	7.7	0.6	0.0	11.9	9.7	3.6	0.2	0.0	11.3	16.8	0.4	0.0	0.0	123.0	127.0	101.0
MAX survival						44.9	44.4	0.0	23.8	0.0	11.2	0.0	7.1	7.1	63.2	16.6	15.7	9.9	1.7	0.0	14.7	12.1	6.2	2.0	0.0	13.2	17.6	1.0	0.0	0.0	88.0	118.0	101.0

Hawsers pretension (t)	Environment heading (deg)	Hs (m)	Tp (s)	Wind Speed (m/s)	Current Speed (m/s)	WEC offset (m)	A-1 Chain Force at anchor Max (t)	A-1 Chain uplift at anchor Max (t)	A-2 Chain Force at anchor Max (t)	A-2 Chain uplift at anchor Max (t)	A-3 Chain Force at anchor Max (t)	A-3 Chain uplift at anchor Max (t)	A-1 pigtail tension Max (t)	A-2 pigtail tension Max (t)	A-3 pigtail tension Max (t)	A-1 sinker5 Z range (m)	A-1 sinker4 clearance (m)	A-1 sinker3 clearance (m)	A-1 sinker2 clearance (m)	A-1 sinker1 clearance (m)	A-2 sinker5 Z range (m)	A-2 sinker4 clearance (m)	A-2 sinker3 clearance (m)	A-2 sinker2 clearance (m)	A-2 sinker1 clearance (m)	A-3 sinker5 Z range (m)	A-3 sinker4 clearance (m)	A-3 sinker3 clearance (m)	A-3 sinker2 clearance (m)	A-3 sinker1 clearance (m)	A-1 Chain TDP min position from anchor (m)	A-2 Chain TDP min position from anchor (m)	A-3 Chain TDP min position from anchor (m)
4	180	1.5	5.5	28.9	1.04	18.6	17.3	0.0	7.6	0.0	11.7	0.0	4.9	4.4	5.4	6.1	8.1	2.1	0.0	0.0	1.5	2.8	0.0	0.0	0.0	3.5	13.7	0.0	0.0	0.0	107.0	122.0	91.0
4	230	1.5	5.5	28.9	1.04	12.9	12.1	0.0	1.6	0.0	11.3	0.0	4.6	4.4	5.9	4.6	5.0	0.0	0.0	0.0	4.2	6.5	1.0	0.0	0.0	3.5	3.3	0.0	0.0	0.0	122.0	105.0	91.0
4	180	1.5	7.5	28.9	1.04	15.3	13.7	0.0	7.0	0.0	10.4	0.0	5.0	3.9	4.4	5.6	6.2	0.7	0.0	0.0	2.7	0.5	0.0	0.0	0.0	1.8	3.0	0.0	0.0	0.0	112.0	125.0	93.0
4	230	1.5	7.5	28.9	1.04	12.4	11.5	0.0	9.2	0.0	10.1	0.0	4.7	4.5	5.1	5.0	3.4	0.0	0.0	0.0	4.7	4.2	0.0	0.0	0.0	1.9	2.2	0.0	0.0	0.0	124.0	117.0	98.0
4	180	4.5	12.5	28.9	1.04	34.1	35.1	0.0	7.3	0.0	10.3	0.0	5.7	5.1	4.7	13.1	13.6	7.7	0.0	0.0	4.7	3.7	0.0	0.0	0.0	11.0	16.9	0.5	0.0	0.0	70.0	118.0	86.0
4	230	4.5	12.5	28.9	1.04	33.6	19.7	0.0	21.4	0.0	9.9	0.0	6.4	6.3	18.1	12.4	9.2	2.8	0.0	0.0	11.5	9.9	3.7	0.3	0.0	9.0	3.3	0.0	0.0	0.0	105.0	94.0	95.0
4	180	4.5	14.0	28.9	1.04	25.8	23.2	0.0	7.1	0.0	9.3	0.0	5.7	4.7	4.2	11.4	10.4	4.1	0.5	0.0	8.4	2.2	0.0	0.0	0.0	8.1	6.0	0.4	0.0	0.0	93.0	120.0	86.0
4	230	4.5	14.0	28.9	1.04	24.1	12.8	0.0	12.9	0.0	8.8	0.0	5.5	5.1	12.9	9.6	6.0	0.5	0.0	0.0	10.0	8.1	2.2	0.0	0.0	6.0	3.4	0.0	0.0	0.0	114.0	103.0	94.0
4	180	6.5	14.4	28.9	1.04	38.5	41.9	0.0	7.6	0.0	9.5	0.0	7.4	9.7	5.1	15.1	15.2	9.3	0.0	0.0	6.6	5.2	0.0	0.0	0.0	12.8	17.5	1.0	0.0	0.0	50.0	118.0	84.0
4	230	6.5	14.4	28.9	1.04	41.4	25.3	0.0	19.9	0.0	13.1	0.0	6.4	6.8	42.0	14.7	11.4	5.2	1.3	0.0	13.4	11.5	5.6	1.6	0.0	10.4	4.1	0.0	0.0	0.0	89.0	86.0	92.0
MAX operational						34.1	35.1	0.0	21.4	0.0	11.7	0.0	6.4	6.3	18.1	13.1	13.6	7.7	0.5	0.0	11.5	9.9	3.7	0.3	0.0	11.0	16.9	0.5	0.0	0.0	124.0	125.0	98.0
MAX survival						41.4	41.9	0.0	19.9	0.0	13.1	0.0	7.4	9.7	42.0	15.1	15.2	9.3	1.3	0.0	13.4	11.5	5.6	1.6	0.0	12.8	17.5	1.0	0.0	0.0	89.0	118.0	92.0

Pretension (t)	Line No.	Hs= 1.5m		Hs= 4.5m		Hs= 6.5m	
		Max (t)	Min (t)	Max (t)	Min (t)	Max (t)	Min (t)
1	1	33.3	4.4	48.7	0.3	55.6	1.2
	2	25.8	-1.1	35.6	-0.1	25.8	-0.2
	3	18.0	0.1	34.3	-5.6	18.5	-0.1
4	1	32.1	5.0	48.6	1.4	53.5	1.0
	2	26.9	-1.7	35.9	-0.1	26.9	-1.7
	3	19.0	1.1	20.3	-4.2	19.0	-0.1
Extremes		33.3	-1.7	48.7	-5.6	55.6	-1.7

Appendix B Results for Berth A – 3 sinkers

Environment heading (deg)	Hs (m)	Tp (s)	Wind Speed (m/s)	Current Speed (m/s)	WEC offset (m)	A-1 Chain Force at anchor Max (t)	A-1 Chain uplift at anchor Max (t)	A-2 Chain Force at anchor Max (t)	A-2 Chain uplift at anchor Max (t)	A-3 Chain Force at anchor Max (t)	A-3 Chain uplift at anchor Max (t)	A-1 pigtail tension Max (t)	A-2 pigtail tension Max (t)	A-3 pigtail tension Max (t)	A-1 sinker5 Z range (m)	A-1 sinker4 clearance (m)	A-1 sinker3 clearance (m)	A-1 sinker2 clearance (m)	A-1 sinker1 clearance (m)	A-2 sinker5 Z range (m)	A-2 sinker4 clearance (m)	A-2 sinker3 clearance (m)	A-2 sinker2 clearance (m)	A-2 sinker1 clearance (m)	A-3 sinker5 Z range (m)	A-3 sinker4 clearance (m)	A-3 sinker3 clearance (m)	A-3 sinker2 clearance (m)	A-3 sinker1 clearance (m)	A-1 Chain TDP min position from anchor (m)	A-2 Chain TDP min position from anchor (m)	A-3 Chain TDP min position from anchor (m)
180	1.5	5.5	28.9	1.04	22.6	18.7	0.0	7.4	0.0	8.8	0.0	#N/A	#N/A	#N/A	#N/A	#N/A	5.1	0.5	0.0	#N/A	#N/A	3.4	0.2	0.0	#N/A	#N/A	10.9	4.2	0.3	95.0	117.0	85.0
230	1.5	5.5	28.9	1.04	21.1	14.3	0.0	13.1	0.0	6.9	0.0	#N/A	#N/A	#N/A	#N/A	#N/A	2.1	0.0	0.0	#N/A	#N/A	1.0	0.0	0.0	#N/A	#N/A	7.7	1.5	0.0	107.0	102.0	99.0
180	1.5	7.5	28.9	1.04	18.4	12.3	0.0	5.7	0.0	8.0	0.0	#N/A	#N/A	#N/A	#N/A	#N/A	2.9	0.0	0.0	#N/A	#N/A	1.6	0.0	0.0	#N/A	#N/A	8.6	2.3	0.0	106.0	119.0	87.0
230	1.5	7.5	28.9	1.04	17.1	11.1	0.0	11.1	0.0	7.1	0.0	#N/A	#N/A	#N/A	#N/A	#N/A	0.1	0.0	0.0	#N/A	#N/A	0.0	0.0	0.0	#N/A	#N/A	5.1	0.0	0.0	119.0	107.0	96.0
180	4.5	12.5	28.9	1.04	36.3	38.2	0.0	5.0	0.0	8.1	0.0	#N/A	#N/A	#N/A	#N/A	#N/A	11.0	5.8	2.2	#N/A	#N/A	9.2	4.9	2.0	#N/A	#N/A	16.1	10.0	5.4	50.0	117.0	85.0
230	4.5	12.5	28.9	1.04	38.2	22.2	0.0	21.8	0.0	6.4	0.0	#N/A	#N/A	#N/A	#N/A	#N/A	6.7	1.6	0.0	#N/A	#N/A	4.9	1.1	0.0	#N/A	#N/A	12.5	5.8	1.3	89.0	85.0	96.0
180	4.5	14.0	28.9	1.04	29.9	22.3	0.0	4.8	0.0	7.2	0.0	#N/A	#N/A	#N/A	#N/A	#N/A	7.5	2.4	0.0	#N/A	#N/A	5.7	1.8	0.0	#N/A	#N/A	13.2	6.6	2.1	87.0	118.0	85.0
230	4.5	12.5	28.9	1.04	38.2	22.2	0.0	21.8	0.0	6.4	0.0	#N/A	#N/A	#N/A	#N/A	#N/A	6.7	1.6	0.0	#N/A	#N/A	4.9	1.1	0.0	#N/A	#N/A	12.5	5.8	1.3	89.0	85.0	96.0
180	6.5	14.4	28.9	1.04	42.7	48.7	0.0	0.3	0.0	7.8	0.0	#N/A	#N/A	#N/A	#N/A	#N/A	13.3	8.4	4.9	#N/A	#N/A	11.6	7.6	4.6	#N/A	#N/A	18.3	12.5	8.0	24.0	110.0	81.0
230	6.5	14.4	28.9	1.04	49.6	32.5	0.0	30.0	0.0	7.3	0.0	#N/A	#N/A	#N/A	#N/A	#N/A	9.7	4.2	1.0	#N/A	#N/A	7.8	3.4	0.8	#N/A	#N/A	15.1	8.7	3.8	66.0	52.0	96.0
MAX operational					38.2	38.2	0.0	21.8	0.0	8.8	0.0	#N/A	#N/A	#N/A	#N/A	#N/A	11.0	5.8	2.2	#N/A	#N/A	9.2	4.9	2.0	#N/A	#N/A	16.1	10.0	5.4	119.0	119.0	99.0
MAX survival					49.6	48.7	0.0	30.0	0.0	7.8	0.0	#N/A	#N/A	#N/A	#N/A	#N/A	13.3	8.4	4.9	#N/A	#N/A	11.6	7.6	4.6	#N/A	#N/A	18.3	12.5	8.0	66.0	110.0	96.0

Line	Hs= 1.5m		Hs= 4.5m		Hs= 6.5m	
No.	Max (t)	Min (t)	Max (t)	Min (t)	Max (t)	Min (t)
1	29.3	2.7	47.9	-0.1	56.5	-1.0
2	22.4	0.6	33.1	-0.2	40.4	-0.9
3	15.2	-0.4	11.9	-2.4	13.3	-6.7
1	31.4	3.6	48.7	1.6	55.4	-0.1
2	24.0	0.9	34.4	-0.2	38.7	-0.4
3	16.4	0.0	15.3	-1.3	16.1	-1.2
Extreme	31.4	-0.4	48.7	-2.4	56.5	-6.7

Appendix C Results for Berth A – no sinkers

Environment heading (deg)	Hs (m)	Tp (s)	Wind Speed (m/s)	Current Speed (m/s)	WEC offset (m)	A-1 Chain Force at anchor Max (t)	A-1 Chain uplift at anchor Max (t)	A-2 Chain Force at anchor Max (t)	A-2 Chain uplift at anchor Max (t)	A-3 Chain Force at anchor Max (t)	A-3 Chain uplift at anchor Max (t)	A-1 pigtail tension Max (t)	A-2 pigtail tension Max (t)	A-3 pigtail tension Max (t)	A-1 sinker5 Z range (m)	A-1 sinker4 clearance (m)	A-1 sinker3 clearance (m)	A-1 sinker2 clearance (m)	A-1 sinker1 clearance (m)	A-2 sinker5 Z range (m)	A-2 sinker4 clearance (m)	A-2 sinker3 clearance (m)	A-2 sinker2 clearance (m)	A-2 sinker1 clearance (m)	A-3 sinker5 Z range (m)	A-3 sinker4 clearance (m)	A-3 sinker3 clearance (m)	A-3 sinker2 clearance (m)	A-3 sinker1 clearance (m)	A-1 Chain TDP min position from anchor (m)	A-2 Chain TDP min position from anchor (m)	A-3 Chain TDP min position from anchor (m)
180	1.5	5.5	28.9	1.04	24.8	19.5	0.0	6.5	0.0	6.6	0.0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	60.0	107.0	80.0
230	1.5	5.5	28.9	1.04	22.9	15.0	0.0	8.1	0.0	4.3	0.0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	86.0	75.0	98.0
180	1.5	7.5	28.9	1.04	19.6	12.5	0.0	3.1	0.0	4.7	0.0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	83.0	118.0	86.0
230	1.5	7.5	28.9	1.04	17.2	8.8	0.0	8.8	0.0	4.3	0.0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	105.0	94.0	98.0
180	4.5	12.5	28.9	1.04	37.5	41.0	0.0	3.9	0.0	5.9	0.0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	15.0	109.0	75.0
230	4.5	12.5	28.9	1.04	39.9	22.2	0.0	26.4	0.0	3.7	0.0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	50.0	35.0	95.0
180	4.5	14.0	28.9	1.04	32.5	25.8	0.0	3.4	0.0	4.8	0.0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	40.0	110.0	80.0
230	4.5	14.0	28.9	1.04	32.2	13.4	0.0	13.2	0.0	6.2	0.0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	81.0	70.0	97.0
180	6.5	14.4	28.9	1.04	44.4	51.6	0.0	11.1	0.0	6.5	1.0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	0.0	97.0	69.0
230	6.5	14.4	28.9	1.04	52.9	36.2	0.0	31.8	0.0	5.4	0.0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	25.0	15.0	96.0
MAX operational					39.9	41.0	0.0	26.4	0.0	6.6	0.0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	105.0	118.0	98.0
MAX survival					52.9	51.6	0.0	31.8	0.0	6.5	1.0	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A	25.0	97.0	96.0

Line No.	Hs= 1.5m		Hs= 4.5m		Hs= 6.5m	
	Max (t)	Min (t)	Max (t)	Min (t)	Max (t)	Min (t)
1	26.4	2.4	46.2	0.2	56.2	-2.9
2	22.0	-0.9	32.0	-0.5	38.8	-4.8
3	14.6	-2.3	12.1	-4.5	13.1	-6.5
Extreme	26.4	-2.3	46.2	-4.5	56.2	-6.5

Appendix D Results for Berth B

Berth B – line 1 only - 5 sinkers cases

Environment heading (deg)	Hs (m)	Tp (s)	Wind Speed (m/s)	Current Speed (m/s)	B-1 Chain Force at buoy Max (t)	B-1 Chain Force at anchor Max (t)	B-1 Chain uplift at anchor Max (t)	B-1 Chain TDP max position (m)	B-1 Chain TDP min position (m)	B-1 pigtail tension Max (t)	B-1 sinker5 Z range (m)	B-1 sinker4 clearance (m)	B-1 sinker3 clearance (m)	B-1 sinker2 clearance (m)	B-1 sinker1 clearance (m)
180.0	1.5	5.5	28.9	1.04	21.4	8.7	0.0	113.9	92.9	17.7	3.6	0.0	0.0	0.0	0.0
210.0	1.5	5.5	28.9	1.04	23.9	7.3	0.0	115.9	91.9	14.1	7.0	0.0	0.0	0.0	0.0
180.0	1.5	7.5	28.9	1.04	14.6	5.4	0.0	109.9	90.9	7.1	0.5	0.0	0.0	0.0	0.0
210.0	1.5	7.5	28.9	1.04	14.0	4.0	0.0	104.9	89.9	7.8	0.7	0.0	0.0	0.0	0.0
180.0	4.5	12.5	28.9	1.04	16.9	6.3	0.0	112.9	85.9	12.1	3.4	0.0	0.0	0.0	0.0
230.0	4.5	12.5	28.9	1.04	16.4	5.1	0.0	111.9	85.9	20.6	3.3	0.0	0.0	0.0	0.0
180.0	4.5	14.0	28.9	1.04	15.6	5.8	0.0	109.9	85.9	17.9	2.6	0.0	0.0	0.0	0.0
230.0	4.5	14.0	28.9	1.04	16.5	4.8	0.0	111.9	84.9	16.0	3.9	0.0	0.0	0.0	0.0
180.0	6.5	14.4	28.9	1.04	19.3	6.4	0.0	114.9	83.9	16.3	6.3	0.0	0.0	0.0	0.0
230.0	6.5	14.4	28.9	1.04	20.2	4.8	0.0	115.9	80.9	27.4	7.5	0.0	0.0	0.0	0.0
MAX operational					23.9	8.7	0.0	115.9	92.9	20.6	7.0	0.0	0.0	0.0	0.0
MAX survival					20.2	6.4	0.0	115.9	83.9	27.4	7.5	0.0	0.0	0.0	0.0

Berth B – line 1 only - 3 sinkers cases

Environment heading (deg)	Hs (m)	Tp (s)	Wind Speed (m/s)	Current Speed (m/s)	B-1 Chain Force at buoy Max (t)	B-1 Chain Force at anchor Max (t)	B-1 Chain uplift at anchor Max (t)	B-1 Chain TDP max position (m)	B-1 Chain TDP min position (m)	B-1 pigtail tension Max (t)	B-1 sinker5 Z range (m)	B-1 sinker4 clearance (m)	B-1 sinker3 clearance (m)	B-1 sinker2 clearance (m)	B-1 sinker1 clearance (m)
180.0	1.5	5.5	28.9	1.04	17.1	5.8	0.0	123.8	94.9	#N/A	#N/A	#N/A	0.0	0.0	0.0
230.0	1.5	5.5	28.9	1.04	17.6	4.6	0.0	115.9	91.9	#N/A	#N/A	#N/A	0.0	0.0	0.0
180.0	1.5	7.5	28.9	1.04	13.8	3.7	0.0	107.9	91.9	#N/A	#N/A	#N/A	0.0	0.0	0.0
230.0	1.5	7.5	28.9	1.04	13.9	3.3	0.0	103.9	90.9	#N/A	#N/A	#N/A	0.0	0.0	0.0
180.0	4.5	12.5	28.9	1.04	17.4	3.9	0.0	113.9	86.9	#N/A	#N/A	#N/A	0.0	0.0	0.0
230.0	4.5	12.5	28.9	1.04	17.2	3.4	0.0	111.9	85.9	#N/A	#N/A	#N/A	0.0	0.0	0.0
180.0	4.5	14.0	28.9	1.04	14.5	3.6	0.0	109.9	85.9	#N/A	#N/A	#N/A	0.0	0.0	0.0
230.0	4.5	14.0	28.9	1.04	14.4	3.2	0.0	108.9	85.9	#N/A	#N/A	#N/A	0.0	0.0	0.0
180.0	6.5	14.4	28.9	1.04	18.0	5.1	0.0	127.8	85.9	#N/A	#N/A	#N/A	0.0	0.0	0.0
230.0	6.5	14.4	28.9	1.04	18.5	3.6	0.0	118.8	81.9	#N/A	#N/A	#N/A	0.0	0.0	0.0
MAX operational					17.6	5.8	0.0	123.8	94.9	#N/A	#N/A	#N/A	0.0	0.0	0.0
MAX survival					18.5	5.1	0.0	127.8	85.9	#N/A	#N/A	#N/A	0.0	0.0	0.0

Berth B – line 1 only - no sinker cases

Environment heading (deg)	Hs (m)	Tp (s)	Wind Speed (m/s)	Current Speed (m/s)	B-1 Chain Force at buoy Max (t)	B-1 Chain Force at anchor Max (t)	B-1 Chain uplift at anchor Max (t)	B-1 Chain TDP max position (m)	B-1 Chain TDP min position (m)	B-1 pigtail tension Max (t)	B-1 sinker5 Z range (m)	B-1 sinker4 clearance (m)	B-1 sinker3 clearance (m)	B-1 sinker2 clearance (m)	B-1 sinker1 clearance (m)
180.0	1.5	5.5	28.9	1.04	17.1	4.5	0.0	123.8	94.9	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
230.0	1.5	5.5	28.9	1.04	17.5	3.2	0.0	115.9	92.9	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
180.0	1.5	7.5	28.9	1.04	13.8	2.0	0.0	107.9	91.9	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
230.0	1.5	7.5	28.9	1.04	13.9	1.3	0.0	103.9	90.9	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
180.0	4.5	12.5	28.9	1.04	17.4	2.4	0.0	113.9	86.9	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
230.0	4.5	12.5	28.9	1.04	17.2	2.0	0.0	111.9	85.9	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
180.0	4.5	14.0	28.9	1.04	14.5	2.1	0.0	109.9	85.9	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
230.0	4.5	14.0	28.9	1.04	14.4	1.4	0.0	108.9	85.9	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
180.0	6.5	14.4	28.9	1.04	18.0	4.0	0.0	127.8	85.9	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
230.0	6.5	14.4	28.9	1.04	18.4	2.3	0.0	117.8	81.9	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
MAX operational					17.5	4.5	0.0	123.8	94.9	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A
MAX survival					18.4	4.0	0.0	127.8	85.9	#N/A	#N/A	#N/A	#N/A	#N/A	#N/A

Appendix E DNV GL technical note “Mooring integrity review”, (doc. No. L32172 Rev 1)

DNV·GL

Noble Denton marine services

TECHNICAL NOTE

DATE:	15/03/17	**DNV GL REF:**	L32172, Rev 1
CLIENT:	Sea Engineering, Inc.	**CLIENT REF:**	-
ATTN:	Marc Ericksen		
CC:	Luis Vega		
Project:	WETS Mooring system review	**Prepared by:**	Alex Argyros
		Verified by:	Renjeev Kurup
Project No:	10034612	**Approved by:**	Jarett Goldsmith
SUBJECT:	Mooring integrity review		

1 INTRODUCTION

Following the failure of the vacant WETS berth B (80m WD) mooring system and damage to the WETS berth A (60m WD) mooring system with the Fred Olsen Lifesaver device connected, Noble Denton Consultants trading as DNV GL has been requested by Sea Engineering Inc to perform a mooring integrity review of the WETS mooring systems, berth sites A and B.

The overall scope of work will include failure mode investigation making use of OrcaFlex models of both berth A and berth B mooring systems. The outcomes of the mooring integrity review and high level mooring loads analysis will be used to evaluate the current design and provide recommendations on high level modifications to hardware components.

This technical note provides the initial review of the mooring design reports and metocean conditions including:

- Identification of the potential failure modes with the WETS mooring systems (berth sites A and B),
- Review mooring analysis against industry requirements (e.g. checking load cases, safety factor, allowance for marine growth, corrosion) and provide good practice,
- Mooring integrity review of manufacturing (component) records,
- Mooring integrity review of installation records,
- Review inspection report and provide observations of potential anomalies as well as areas for further inspection (if required),
- Provide long term integrity risk areas.

The problem areas summarized in this technical note will be further assessed in the next phases of this project.

2 APPROACH

Our approach for the integrity review is considering the lifecycle phases of the mooring system, these are design, manufacturing, installation and operation / life extension. This report is structured as such.

Figure 2-1 Mooring integrity management lifecycle

The integrity review is performed considering mooring berths A and B in both vacant state and connected to arbitrary wave energy converter (WEC); e.g. Lifesaver. The review is of the intended mooring system design of 2014, Ref. /1/ & /2/ and as-built record, Ref. /3/; recent work from 2016 that simulates the Lifesaver motions in operating conditions due to reduced hawser pretension and loss of sinker #5 (closes to fairlead) is only for information.

2.1 Failure modes

Potential failure modes (FM) are identified which are assigned to the following categories:

- Input Data
- Design Analysis
- Strength
- Wear / Erosion
- Corrosion
- Fatigue
- Contact
- Motion
- Manufacturing
- Deployment

This hazard identification process follows the recommendations given in the Oil & Gas UK Mooring Integrity Guidance, Appendix C, Ref. /16/. The list of potential failure modes that would be generally applicable to the WETS mooring systems (berth sites A and B), based on the location and configuration considered, are shown in Table 2-1.

The design review is subsequently conducted in section 3 for the four lifecycle phases and reflecting on the failure modes identified in Table 2-1. The most important failure modes for the WETS mooring systems (berth sites A and B) are identified in section 4, based on review of the documentation and the long term integrity risk areas presented.

Table 2-1 General failure modes for WETS site A and B

Failure type	Failure mode	Details	ID
Input data	Seabed	Lack of soil data and knowledge of seabed hazards	1.1
	Metocean	Out of date, tidal range unknown, data availability	1.2
	Metocean	Inaccurate metocean analysis input / directionality not accounted	1.3
	WEC	Inaccurate environmental load coefficients	1.4
	Mooring components	Inaccurate stiffness, weight, length and drag properties	1.5
	Specification	Unrepresentative analysis to as-installed line properties	1.6
Analysis	Code	Inappropriate return period	2.1
	Code	Inappropriate safety factor and load cases	2.2
	Method	Inadequate model test validation	2.3
	Method	No cable envelope and lack of protection of subsea assets	2.4
Strength	Safety factor	Code requirement not followed	3.1
	Safety factor	Overloading e.g. due to unbalanced pre-tensions	3.2
	Snatch load	Snatch load on slack lines - highest loads may not be at the top	3.3
	Snatch load	Sudden breakout of hawser / surface buoy	3.4
	Bend radius	Low bend radii on slack lines	3.5
	Means of securing	Security of pins, bolts and other connections	3.6
Wear	With other item	Between mooring component interfaces	4.1
	With other item	Wear against concrete sinkers	4.2
	With seabed	Debris or boulder damage	4.3
	Internal	Wear with internal structure e.g. chain links, fibre strands	4.4
Corrosion	General	Corrosion allowance	5.1
	Accelerated	Galvanic corrosion due to dissimilar metals	5.2
	Accelerated	Splash zone corrosion	5.3
	Accelerated	Microbiological influenced corrosion at seabed	5.4
Fatigue	Axial	Inadequate fatigue load cases and analysis method	6.1
	Axial	Inadequate SN curve (particularly for connectors)	6.2
	Axial	Analysis not undertaken throughout line	6.3
	Bending	Increased fatigue due to chain bending	6.4
	Bending	Sharp inverse catenary angle	6.5
Contact	Vessels	Surface buoy collision with vessel	7.1
	Seabed	High energy causing damage, particularly with boulders and debris	7.2
	Dropped object	From vessel or other	7.3
Motion	Seabed scouring	Reduced soil capacity and anchor resistance	8.1
Manufacturing	Mooring components	Poor choice of components for offshore application	9.1
	QA/QC	Inappropriate material and weld quality	9.2
	QA/QC	Inappropriate heat treatment	9.3
	Welding quality	Inconsistency of welds and material properties	9.4
	Proof loading	Proof load test does not follow code requirements	9.5
Deployment	Damage	Wear, twist or bending damage	10.1

3 DESIGN REVIEW

The mooring analysis and associated documents are reviewed against industry requirements and good practice design recommendations given. The different areas of evaluation are color coded accordingly:

- Acceptable compared to good practice
- Area for design improvement
- Non-compliance to industry practice

Reference is also made to the failure mode IDs, as applicable in this notation [No.]

3.1 Background

The mooring analysis should follow the requirements of an industry standard. Below is an example of the leading standards for mooring analysis of floating structures used by the industry and most applicable to wave and tidal energy converters:

- IEC TS 62600-10:2015 Assessment of mooring systems for marine energy converters (MECs), Ref. /11/
- ISO19901-7:2013 Stationkeeping systems for floating offshore structures and mobile offshore units, Ref. /12/
- DNVGL-OS-E301 Position mooring, Ref. /13/
- API-RP-2SK Design and analysis of stationkeeping systems for floating structures, Ref. /14/

The analysis requirements of the IEC TS 62600-10 are based on ISO19901-7, which has a widely-used application. Common to all standards, the limit states that should be considered by the mooring analysis are listed below:

- ULS – ultimate limit state (survival condition) of the intact mooring system corresponding to system's resistance to extreme environmental action
- ALS – accidental limit state (survival condition) of the damaged mooring system (e.g. one line failure) to ensure system has sufficient redundancy to extreme environmental action
- SLS – serviceability limit state relating to mooring system installation, O&M (operation and maintenance) and decommissioning
- FLS – fatigue limit state of the intact mooring system referring to cumulative damage in the system in survival and operational conditions

Ref. /1/ makes reference to DNV-OS-E301 and API-RP-2SK, however it not explicitly stated which is the governing standard. The ULS and ALS safety factors (SFs) for ISO19901-7 and API-RP-2SK are the same, DNVGL-OS-E301 SFs are different and based on partial SF approach and IEC TS 62600-10:2015 uses an adjusted safety factor approach (see Appendix A – IEC TS 62600-10). The IEC standard, though it has been developed for the assessment of mooring systems for marine energy converters (MECs), only provides high level design guidance, consequently should be used in conjunction with a more established standard such as ISO19901-7.

DNVGL-OS-E301 has been developed over a long period and (in conjunction with other DNV guidelines, such as DNV-RP-C205) provides a high level of detail for designing, installing and maintaining mooring systems for offshore equipment. Its application in this project is considered acceptable.

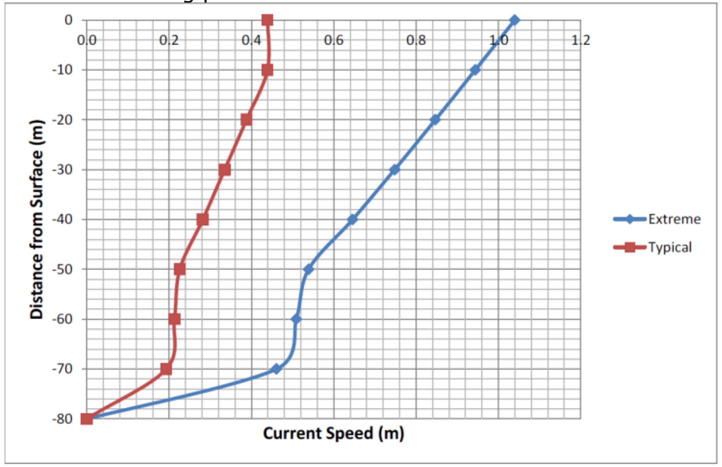
3.2 Mooring analysis

<table>
<tr><th>Item</th><th>Good practice</th><th>Ref report</th><th>Observations</th><th>FM</th></tr>
<tr><td>Seabed modelling</td><td>For long term mooring, sea bed soil conditions shall be determined for the intended site to provide data for the anchor design.</td><td>Ref. /1/</td><td>Water depths were determined across the entire project area with a level of high resolution, however the mooring model does not appear to represent the bathymetry. Site free of boulders and debris.</td><td>[1.1]
[4.3]</td></tr>
<tr><td>Metocean data</td><td>Extreme data for waves should be developed from extensive site measurements and robust analysis of extreme storm events.</td><td>Ref. /4/</td><td>20 years of spectral wave estimates for the Kaneohe Rov7 site are derived based on SWAN version 40.85 used to downscale spectral wave parameters hindcasted from WAVEWATCH III (WW3). It is a good approach, using SWAN to get higher resolution in bathymetry and using wind fields from WRF as input.

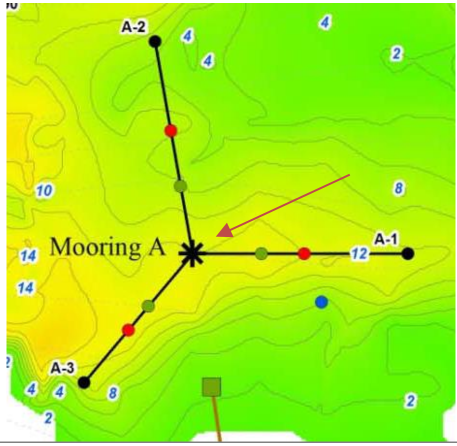
Documentation does not provide resolution of the wind as input in the wave model, the bathymetry resolution and the wave data in output.

Apart from the assumed validation of the NOAA hindcast with measured data, no explicit validation using site measurements is considered in the 100-year design wave.

ADCP and Waverider data from September 2016 show good agreement. These should be used to validate the SWAN and WW3 hindcast.</td><td>[1.2]</td></tr>
<tr><td>Metocean data – WD</td><td>The design water depth for the mooring system at each anchor location shall account for sea level variations due to tides and storm surges.</td><td>Ref. /1/</td><td>No water depth variation included in the analysis. Customer confirms by telecon there are no tidal variations at Kaneohe Rov7 site.</td><td>[1.2]</td></tr>
<tr><td rowspan="2">Metocean data – Wave</td><td>Suitable extreme data for waves is applied using appropriate spectra for the location.</td><td>Ref. /1/
Ref. /4/
Ref. /9/</td><td>100-year design wave Hs used in the design report does not match the metocean report. Reference to 13.5 m Hs in the analysis results - lack of clear understanding of the design environment.
<table><tr><th>Source</th><th>Hs (m)</th><th>Tp (s)</th></tr><tr><td>Design report Ref. /1/</td><td>5.53</td><td>15.79</td></tr><tr><td>Metocean report Ref. /4/</td><td>6.50</td><td>14.40</td></tr></table></td><td>[1.3]</td></tr>
<tr><td>Suitable extreme data for waves is applied using appropriate spectra for the location.</td><td>Ref. /1/
Ref. /4/
Ref. /9/</td><td>"Rule of thumb" Tp range for Hs 6.5m would be approximately 9.5sec-14sec. Tp range considered 10sec-15.8sec is acceptable and covers the 100-year design Tp considered for OEL WEC device.</td><td>[1.3]</td></tr>
</table>

Item	***Good practice***	***Ref report***	***Observations***	***FM***
	Suitable extreme data for waves is applied using appropriate spectra for the location.	Ref. /2/	Spectral shape parametric study performed, shows gamma=1 causes higher tension than gamma 3.3, for range of Tp (11sec-15sec) covering the 100-year design Tp. Definition of the design wave spectrum taken as PM spectrum (i.e. JONSWAP with gamma equal to 1.0) is conservative.	[1.3]
	Directionality is accounted for.	Ref. /1/	Each mooring leg is designed to take the entire survival loading.	[1.3]
Metocean data – Wind	Wind data appropriate to the location should be applied and should refer to an elevation of 10m above still water level. Two analytical approaches may be used to represent wind actions (as per ISO 19901-7): - constant in direction and speed, taken as the 1-min average; - 1-hour average velocity, plus a time-varying component calculated from a suitable empirical wind gust spectrum.	Ref. /1/ Ref. /2/ Ref. /10/	The design report specifies 10-min wind speed is applied equal to 26.1m/s; based on to DNV-RP-C205 this corresponds to 1-minute wind speed equal to 28.9m/s that should be used. Windage area of the Lifesaver WEC is minimal and so wind load effect expected to be small. For WEC with exposed windage correct definition should be used.	[1.3]
Metocean data – Current	Current data appropriate to the location should be applied.	Ref. /1/ Ref. /2/ Ref. /6/ Ref. /10/	The design report specifies surface current speed equal to 1.044m/s with the following profile considered.  September 2016 ADCP data shows surface currents flow in a predominantly westerly direction with average speed of 0.24 m/s, and a maximum recorded speed of 0.67 m/s. Design current speed is acceptable.	[1.3]

Item	***Good practice***	***Ref report***	***Observations***	***FM***
Wave response	Low frequency (LF) and wave frequency (WF) loads modelled using analytical models where the wave response is validated using model tests.	Ref. /1/ Ref. /2/	AQWA used to model the mooring buoy and WEC devises that intrinsically models WF and LF loads. Mooring arrangement de-couples the WF motions from the line dynamics, consequently mean loading is major contributor to WETS chain mooring tension (i.e. mean wave drift, current and wind load).	[1.4]
Wind and current loading	Wind and current loads derived from wind tunnel tests.	Ref. /1/ Ref. /2/	No specification of WEC and surface buoy current load coefficients.	[1.4]
Mooring modelling	Full documentation of mooring model inputs that represents as-laid mooring system.	Ref. /1/ Ref. /2/	Mooring modelling input not documented.	[1.5]
Anchor capacity	Design load and holding capacity clearly defined for all limit state conditions. Soil conditions derived from detailed site survey. Holding capacity determined from standard design tables and confirmed from anchor manufacturer and/or holding capacity analysis for site specific conditions.	Ref. /1/ Ref. /5/	Thorough geotechnical survey performed, however, anchor ultimate holding capacity determined based on Bruce MK4 standard chart. Based on the chart (figure 33) for a 9 tonne anchor (19.8kips) the ultimate holding capacity is 2003kN (450kips), not 2850kN as stated in the design report. The corresponding tension limit is given in section 3.2.1	[1.6]
Design standard	Design follows the requirements of an applicable industry standard and has been quality assured by independent party.	Ref. /1/	Reference is made to DNV-OS-E301 and API-RP-2SK, however it not explicitly stated which is the governing standard and no specification of design criteria. No verification from Independent Competent Person (ICP).	[2.1]
Return period	Survival seastate 100-year wind, wave or current with appropriate associated conditions.	Ref. /1/	50 to 100-year wave conditions considered.	[2.1]
Safety factor (see A.2)	Safety factors in accordance with modern design code requirements and consequence of failure. Application of DNVGL-OS-E301 or ISO19901-7. Alternative approach shown in Appendix A – IEC TS 62600-10	Ref. /1/	Factor of safety for mooring lines is taken as 2.1, on peak load for wet breaking strength assuming the system is intact. This corresponds to DNVGL-OS-E301 (only dynamic factor) so is conservative with regards to application of DNVGL-OS-E301. Anchor factor of safety is taken as 1.5, against drag; dynamic. This corresponds to ISO19901-7 ULS (see Table A-3). Acceptable.	[2.2] [3.1]
Analysis method	Appropriate dynamic analysis method to capture extreme value motion and force response. Extreme value estimation sufficient to capture response and statistical variability.	Ref. /1/ Ref. /2/	A number of design data and results are missing: • Mooring analysis for the no WEC connected case (slack lines), • Extreme value analysis of multiple realizations of 3-hour time domain simulations to calculate most probable maximum tension, • ALS case, including verification of cable watch circle in ALS, • Documentation of drag coefficient and marine growth allowance[1].	[2.4] [3.3]

Item	Good practice	Ref report	Observations	FM
	Analysis of operational scenarios and documentation of analyses.	Ref. /1/ Ref. /2/	Design data / results to improve design assessment: • Model test validation, • Load case definition of headings, Hs and Tp considered, • Transient breakout analysis, • Confirmation that cable dynamics module of AQWA is used to perform the mooring analysis, • Anchor position sensitivity study considering plate anchors are positioned within 5m of the specified locations.	[2.3] [3.4]
Tension balance	Balanced pre-tensions to share load.	Ref. /7/	Berth A (60 m depth) LifeSaver mooring modifications, hawser lengths were replaced and shortened by 20-ft on 9 Nov 2016. New lengths are listed below: A1 = 94.5m A2 = 93.9m A3 = 84.1m The design document was not changed to reflect new lengths. Predominant wave direction between lines A-1 and A-2; A-3 tightened to take up slack, however corresponding increase to A-1 and A-2 pretension not proven. 	[1.6] [3.2]
Corrosion and wear allowance[2]	Allowance based on industry experience for the component loading regime and geographical region.	Ref. /1/	There is no corrosion allowance. No wear allowance. • Use of clump weights in mooring design requires consideration of large angle change to the mooring line at a single point and	[4.1] [4.2] [3.5] [3.6] [5.1]

Item	*Good practice*	*Ref report*	*Observations*	*FM*
			thus localised wear may be significantly increased. • Local wear of connecting mooring chain link due to bending caused by eccentric loading and abrasion with the sinker. • Dynamic response of sinkers and interaction with the seabed which can result in damage or loss of the clump weight. Design of plasma hawser not scope of original WETS mooring design.	
Fatigue	Fatigue assessment performed with consistent safety factor in accordance with modern design code requirements. Bending fatigue as applicable included in the analysis based on latest industry guidance and verified by laboratory tests. Realistic representation of long term metocean conditions and operating modes.	Ref. /1/	No fatigue analysis performed.	[6.1] [6.2] [6.3] [6.4] [6.5]
Clearance	Mooring equipment remains clear of subsea assets with an appropriate margin. Sensitive equipment clear of seabed contact.	Ref. /1/ Ref. /2/	No clearance studies performed. Greenfield site and moorings clear of cable route so not applicable.	[7.2]

[1] Site specific marine growth estimation will be considered in the next phase of this work

[2] Site specific corrosion allowance based on the WETS seawater chemical analysis survey form will be considered in the next phase of this work

3.2.1 ULS Tension checks

Below is a list of ULS tension results from Ref. /1/ and /2/ which are compared to chain MBL and anchor holding capacity design requirement per ISO 19901-7 safety factors (see section A.2). It is not clear from the reports what are the design tensions, how these are code checked and confirmation of compliance.

Table 3-1 ULS tension results from Ref. /1/ and /2/

Case & source	Site	Hs (m)	Tp (s)	Chain top tension				Anchor check			
				Hawser tension[1] (kN)	Chain MBL[7] (kN)	SF	SF req.	Anchor tension[2] (kN)	Anchor UHC[3] (kN)	SF	SF req.
Largest OEL design load[4] ref. /1/	B	5.53	11	1050	3690	3.51	1.67	977	2003	2.05	1.50
OEL broadside ref. /1/	B	5.53	11	1900	3690	1.94	1.67	1827	2003	1.10	1.50
ADM-4 figure 7, ref. /2/	B[5]	6.50	11	720 [6]	3690	5.13	1.67	647	2003	3.10	1.50
ADM-4 figure 7, ref. /2/	B[5]	13.50	11	1390 [6]	3690	2.65	1.67	1317	2003	1.52	1.50

[1] Assumed that analysis is dynamic and not quasi-static

[2] Approximated as top tension minus WD*submerged weight of chain, i.e. ignores tension loss due to friction

[3] Ultimate holding capacity (UHC)

[4] Stated in the main text "*In the Site 2 Mooring 'B', the design loading is 236 kips (1,050 kN) for the OEL device*"

[5] Assumed site B

[6] For gamma=1 and pretension 40kN

[7] Based on ABS rules Ref. /15/

3.2.2 Anchor holding capacity

The figure below from ISO19901-7 confirms the anchor ultimate holding capacity is 2003kN (450kips).

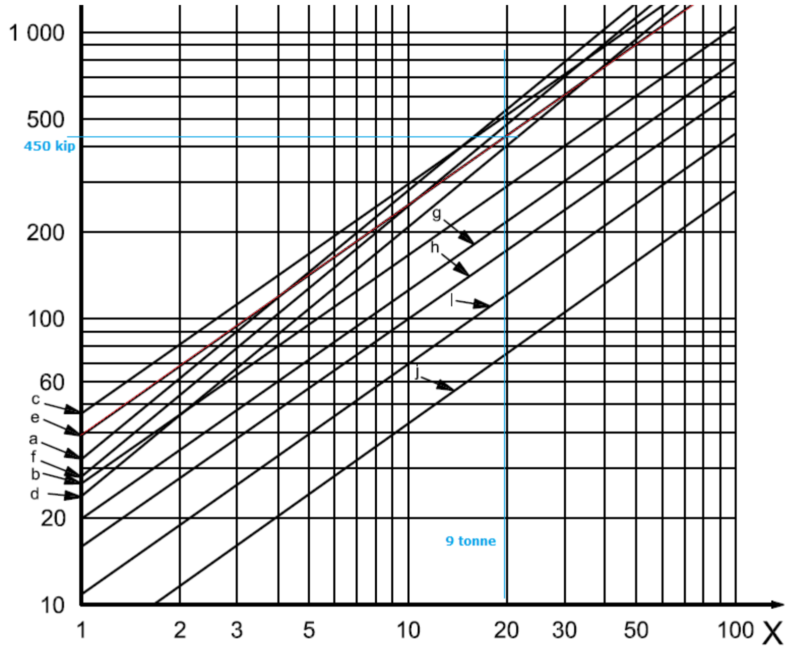


Figure 3-1 Anchor system holding capacity in sand ISO19901-7, Ref. /12/

3.3 Manufacturing

The major hazards observed in the manufacturing records Ref. /17/ to /30/ provided to DNV GL are listed below (a full list is given in Table 3-2).

- Most of the equipment employed are not suitable for long term offshore mooring.
- There are no established fatigue characteristics for these items, hence require routine inspections, which may involve retrieval of anchors, as typically carried out for naval moorings.
- Detailed manufacturing records not available for chain and other accessories, only certificates available.
- Specification of the detachable connecting link is not clear.

Table 3-2 Manufacturing records observations

Item	Maker	Specification	Certification	Comments
Bruce FFTS Anchor	Bruce	9000 kg Bruce Mk 4 anchor, proof loaded to 3060 kN (312 te)	ABS	
Bruce Dee type Anchor Shackle	Bruce	120mm leg dia. forged shackle, R4 grade, 400 te proof load	ABS & DNV (type approved)	Not approved for permanent mooring – temporary/mobile mooring only requiring regular inspection.
Detachable anchor joining Link (No. 7 Pear Link?)	ACSA	79mm nominal dia. ABS Grade 3b (cast steel), MBL – 4962 kN (505 te)	ABS certificate	Drawings/detailed specifications not available. If Pear Link, not suitable for long term mooring.
Mooring Chain	Jiangsu Asian Star Anchor Chain Co. Ltd / Quingdao Anchor Chain factory	2.75" nominal dia. stud link ABS Grade 3a, break test – 826000 lbs (375 te)	ABS certificate	Marine Grade chain, not suitable for long term mooring, unless inspected regularly – See class inspection regime. Fatigue characteristics are not established. Limited non destructive testing (NDT) during manufacture.
Kenter Links/Connecting Links	Unknown	2.75" nominal dia. ABS Grade 3	No certificates available	Kenter links are not suitable for long term mooring. Routine inspection required.
Sinker Shackle	FASTENAL/LISTER	2.75" nominal dia. proof load applied – 862000 lb. (375 te) Shackles 1, 26 only proof loaded to 200,000 lb. (91 te)	No product certificate available and not type approved. Proof test and material certificate only.	Detailed drawing not available. Sketch available in Drawing No. 3203-300-200 does not show any double securing of nuts. The close fit up as shown in the sketch does not appear suitable for dynamic environment.
Tri-plate	Unconfirmed (Washington Chain & Supply)	2.75", #2 Proof load of 485000lbs (220 te) MBL – unknown.	No certificates available	Not intended for long term mooring unless fatigue characteristics established. Mainly used for towing operations. Routine inspections of the tri-plate mitigate failure for towing operation.
Tow shackle	Unconfirmed (Washington Chain & Supply)	2.75", #210 WLL – 85 te, MBL – 510 te (calculated with factor of safety of 6)	No certificates available	Not intended for long term mooring unless fatigue characteristics established. Mainly used for towing operations and construction lifting activities. Routine

Item	Maker	Specification	Certification	Comments
				inspections of the shackle mitigate failure for towing operation.
Plasma hawser	CORTLAND	3.25” 40ft long pigtail assembly. 940000 lbs (427 te) breaking load (estimated)	No certificates available.	Type approved. Susceptible to strength reduction due to kink, especially when disconnected and secured to buoy. Product specification by manufacturer does not include offshore mooring application. Similar HMPE ropes are used for offshore mooring.
Buoy Shackle	Marine Fender International	3” Safety Shackle	No certificates available.	Details not available.
Buoy	Marine Fender International	12ft dia. 75kips (34 te) net buoyancy buoy	No certificates available.	As-built data, details not available.

* te = metric tonnes

3.4 Installation

The major hazards observed in the installation record Ref. /3/ provided to DNV GL are listed below:

- No documentation that anchor positions and tensions are within installation tolerances. Deviation of as-built and design location of mooring anchors, see section 3.4.1.
- No hold points were indicated in the documentation and there was limited or no oversight of the installation contractor.
- No documentation of measured as-installed tensions for lines 1 and 2 of each mooring berth, see section 3.4.2.
- Increased installation complexity of sinkers and ensuring alignment not addressed by procedures through risk assessment and identification of potential integrity risks, such as excessive twist.
- There is no baseline survey with ROV footage for each component after installation revealing the as-laid integrity status and giving a baseline for future inspections.
- No management of change documentation and record of observed anomalies in as-laid survey report. Mooring analysis not re-assessed with measured data.
- The mooring make up drawing instructs to secure all shackles except Marquip shackles to be welded and secured. Grade 3 materials are heat treated and hence no welding should be carried out unless heat treated after welding.

3.4.1 As-built record

A fix is taken on the location of as-laid mooring components. Table 3-3 compares the locations of the anchors, as-built Ref. /3/ to design Ref. /1/. This shows a maximum of 9.80m deviation of the anchor location from design.

Table 3-3 Anchor locations

Anchor	Design X (m)	As-built X (m)	DX (m)	Design Y (m)	As-built Y (m)	DY (m)
A1	629434.00	629443.77	9.77	2375147.96	2375147.96	0.00
A2	629058.00	629055.85	-2.15	2375463.00	2375471.89	8.89
A3	628952.85	628947.95	-4.90	2374956.39	2374950.99	-5.40
B1	628731.70	628740.84	9.14	2375633.80	2375633.80	0.00
B2	628262.31	628260.71	-1.60	2376027.69	2376036.70	9.01
B3	628074.59	628068.72	-5.87	2375327.40	2375320.40	-7.00

3.4.2 Mooring proof load

Ref. /2/ states the anchors are proof loaded in 25 ton(long) increments to 100 ton(long), i.e. 890kN and held for five minutes. ISO 19901-7, section 10.4.6.2 requires that in sandy conditions proof load should be 100% ULS load. From Table 3-1 the design hawser load is 1050kN therefore the proof load only represents 85% ULS load.

The mooring proof load test setup explained in Ref. /3/ is depicted in Figure 3-2. For each berth, line 3 is connected to the winch line connection and proof loaded to target sustained test load of 90 ton(long). A load cell monitors this load. Lines 1 and 2 are connected to the barge using anchor shackle padeyes. It is stated that the 90 ton(long) load in leg 3 would result in a 106 ton(long) in legs 1 and 2.[1]

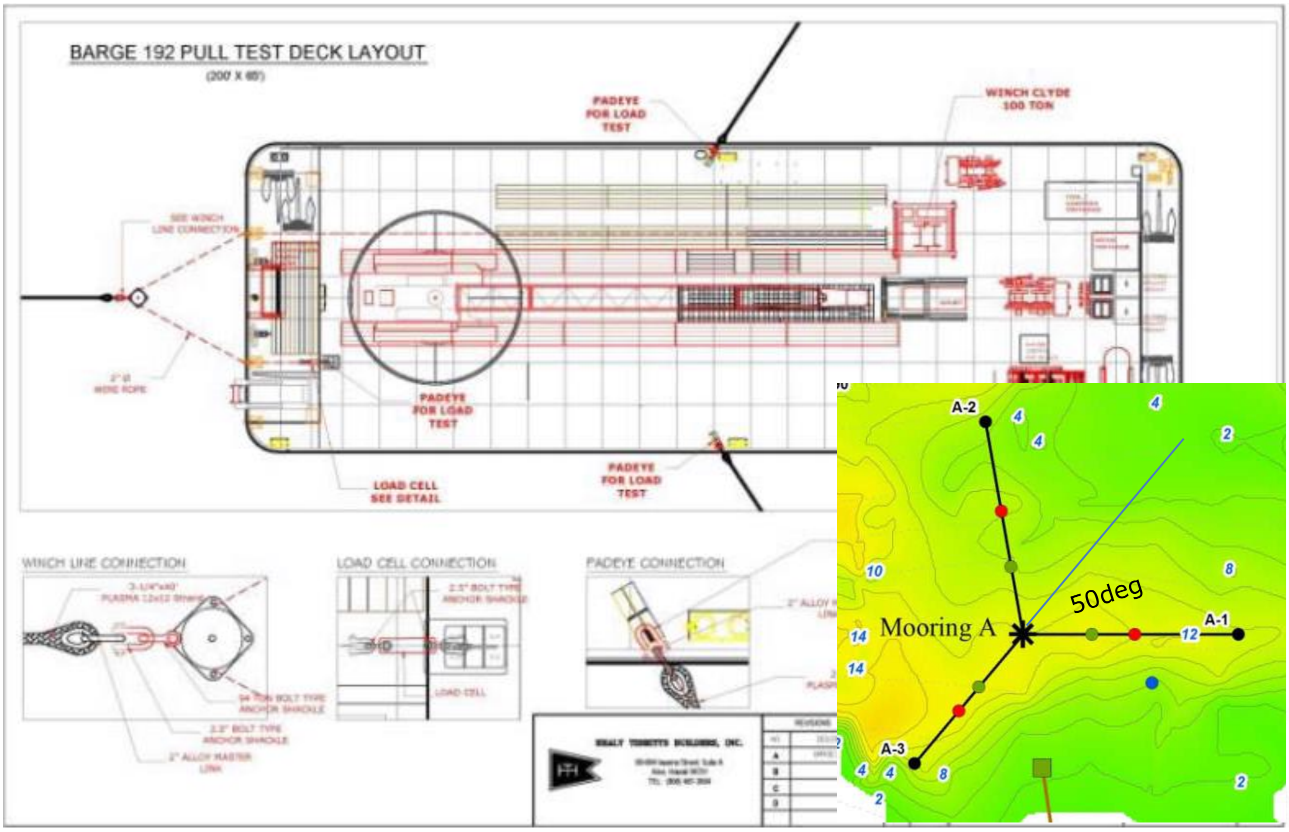


Figure 3-2 Barge deck layout for proof test

The issues with this proof load test setup are:

- Based on geometry the angle between legs 1 and 2 is 100 degrees, hence the dissecting angle of leg 3 with legs 1 and 2 is 50 degrees. To achieve 100 ton(long) in legs 1 and 2 requires 129 ton (long) in leg 3.
- Only leg 3 load is monitored, and it is assumed there is equal load distribution between legs 1 and 2. The proof load on each mooring line should be proven and documented.

[1] 90 ton(long) load in leg 3 will only equate to 70 ton(long) load in legs 1 and 2.

3.5 Operation

The major hazards regarding the operation of the WETS mooring sites are listed below:

- Ref. /1/ states that both the deployment and operational requirements of typical WEC devices were considered as part of the final "universal" mooring configuration (i.e. it was important to consider how WEC devices will be connected/disconnected from the mooring). However, no description of the stowage plan of the berth site without WEC is provided.
- The design documents do not recommend an inspection plan (ideally risk based for the most vulnerable items).
- There is not monitoring plan, or interface management plan with the WEC developers for how to handle the mooring system.
- The inspection report is of good quality with clear imaging (commentary given in section 3.5.1), however there are no measurements of components.

3.5.1 Inspection notes

The major observations from the inspection report Ref. /8/ provided to DNV GL are listed below:

Item	Observations	Failure Type	Failure Mode	Comments	Recommendations
Bruce FFTS Anchor	No anomalies noticed Fluke below mudline, shank exposed.	Soil	Seabed Scouring	Scour noticed around mooring line and sinker weights. Soil consists of loose sand.	1. Periodical survey to ensure that the anchor flukes are not exposed.
Bruce Dee type Anchor Shackle	Not Visible, buried	-		-	2. Periodical survey to identify any anomalies/scour.
Detachable anchor joining Link (No. 7 Pear Link?)	Not Visible, buried				3. Periodical survey to identify any anomalies/scour.
Mooring Chain	Broken/disconnected Chain (B1 and B2)	Strength Fatigue	Means of Security Overload Axial and/or Bending Fatigue	Actual failure mechanism to be confirmed.	4. Recover failed/opened links and investigate failure mechanism so that mitigation measures can be implemented. 5. Replace with long term mooring (LTM) connectors with means of double securing arrangement. 6. Avoid connecting links at thrash zone 7. Use offshore grade chain
	Loose Studs (applicable for all moorings)	Wear/Erosion	Contact with sinker/seabed	Fatigue cracks can initiate at the stud location. Loose studs are observed only above sinker no. 5 indicating damage before connecting WEC due to localised contact with sea-bed.	8. Avoid sinkers in the thrash zone in the dynamic section of the chain 9. Recover objects that can cause wear
		Fatigue	Axial		10. Material selection – use studless link chains to avoid stress concentration
	Material loss and wear	Wear/Erosion	Contact with another item (sinker) Contact with seabed		11. Avoid sinkers in the thrash zone in the dynamic section of the chain
	Sinker sitting on chain	Strength Wear/Erosion	Bending Material loss due to contact with sinker		12. Reposition the mooring chain/sinker to avoid contact. Sinkers should be lifted from sea-bed only in the event of

					extreme events.
	Chain sitting over sink (Figure 3-3)	Strength Wear/Erosion	Bending Material loss due to contact with sinker		13. Reposition the mooring chain/sinker to avoid contact. Sinkers should be lifted from sea-bed only in the event of extreme events.
	Large crater under the buoy (Figure 3-6, Figure 3-7)	Motion	Seabed Scouring	Localised motion when the buoy is not attached to WEC.	14. Modify the system to avoid localised contact of the mooring chain with sea-bed. (Design Change)
	Chain appears to have twisted (A3), (Figure 3-8).	Fatigue	Torsion	It appears that during reconnection, the torsion from the plasma rope has rotated the buoy and transferred across to the catenary section	15. For connecting WEC/handling during the operation, use non-rotational ropes or use swivels to avoid twist onto the Plasma rope
Kenter Links/Detachable connecting Links	Potential loss of kenters on B1 and B2 (Figure 3-5)	Strength	Means of Security	Mooring leg B2 potentially disconnected at open kenter link (*no ROV footage available*)	16. Close Visual Inspection (CVI) of all kenters in the catenary 17. Routine inspections (NDT) 18. Replace with long term mooring (LTM) connectors with double securing arrangement where practically possible. 19. Avoid connectors in the thrash zone
	Deployment	Deployment	Welding/Heat Treatment	Doc No. 0001B WETS Final Design Appendix B-5 requires all anchor joining links and chain joining links to be secured with lead and/or welding.	20. Avoid welding of heat treated components (Grade 3), replace any components welded during installation phase.
Sinker Shackle	Potential damage to sinker shackle (All moorings except B3, A3)	Strength	Axial Snatch Load Bending	Loading varies depending on the position of the sinker. Sinker shackles are (Sinker No. 4 & 5) are constantly subjected to dynamic loads. Loading is not always axial.	21. Avoid sinkers in the thrash zone in the dynamic section of the chain.
		Fatigue	Axial Bending	Failure mode of the sinker shackle pins are not	22. Use long term mooring connectors (LTM)

				established.	23. Recover sinker shackle pins and carry out investigation into the failure mode
Tri-plate	Orientation of the tri-plate (Figure 3-9)	Deployment		Tri-plate orientation does not consider the direction of maximum load	24. Check line segment with maximum mooring load and reinstall the tri-plate if required.
		Wear/Erosion	Contact with Tow shackle	General visual survey indicates substantial movement between the tri-plate and the tow shackle, especially to the buoy.	25. Periodical survey to mitigate failure due to material loss
Tow shackle	Eccentricity in the loading of the shackle (Figure 3-11)	Deployment	Unintended load path	The clearance between the jaw of the shackle and mooring link causes the shackle to tilt and induce side load.	26. Consider spacers/re-size shackles to suit
Plasma hawser	Potential loss of strength, rope twisted and flattened. See (Figure 3-4, Figure 3-12)	Deployment	Torsion	When secured to the top of the buoy, the hawser appears to have twisted around the riser chain to the buoy and flattened.	27. For connecting WEC/handling during the operation, use non-rotational ropes or use swivels to avoid twist onto the Plasma rope
Buoy Shackle	No anomalies noticed			CVI not available	
Buoy	No anomalies noticed			CVI not available	

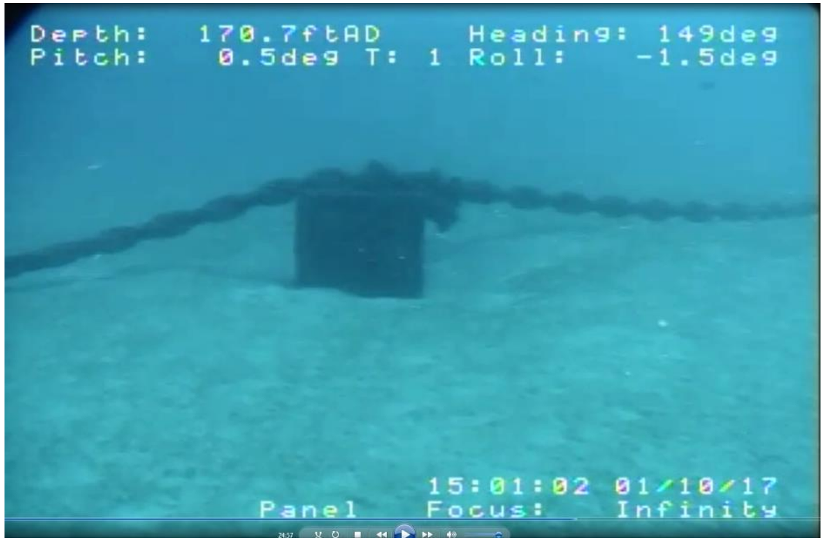


Figure 3-3 Chain Sitting on Sinker (B3)

Figure 3-4 Plasma Rope twisted around mooring chain

Figure 3-5 Disconnected Kenter (B2), from Doc. 0008A 2017 ROV Photos

Figure 3-6 Chain disappearing into crater under the buoy (B3)

Figure 3-7 Crater at Sinker 5 (B3), touchdown contact with seabed due to the presence of sinker when no WEC attached.

Figure 3-8 Loose studs and twisted chain (A3)

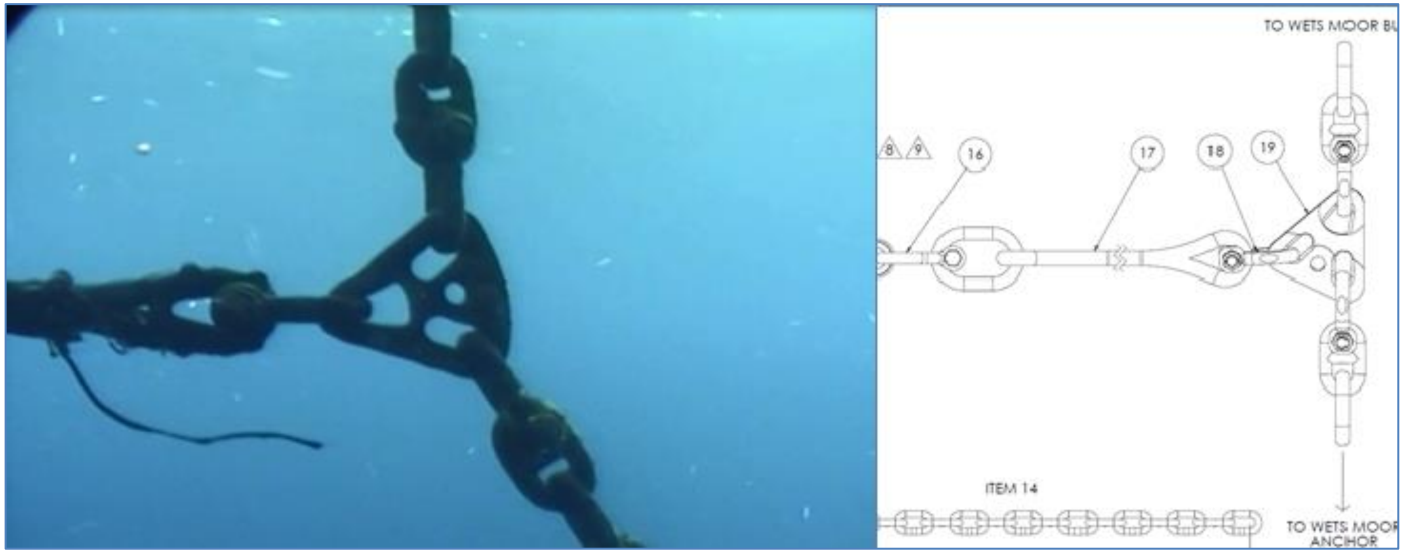


Figure 3-9 Orientation of Tri-plate (Tow Plate)

Figure 3-10 Contact with Sinker (A3)

Figure 3-11 Eccentricity in shackle loading

Figure 3-12 Twisted and flattened Plasma Rope

Figure 3-13 Sinker Sitting on Chain (B2)

4 LONG TERM INTEGRITY RISK AREAS

The figure below provides the most important failure modes and long term integrity risk areas for WETS mooring systems berth sites A and B based on review of the documentation.

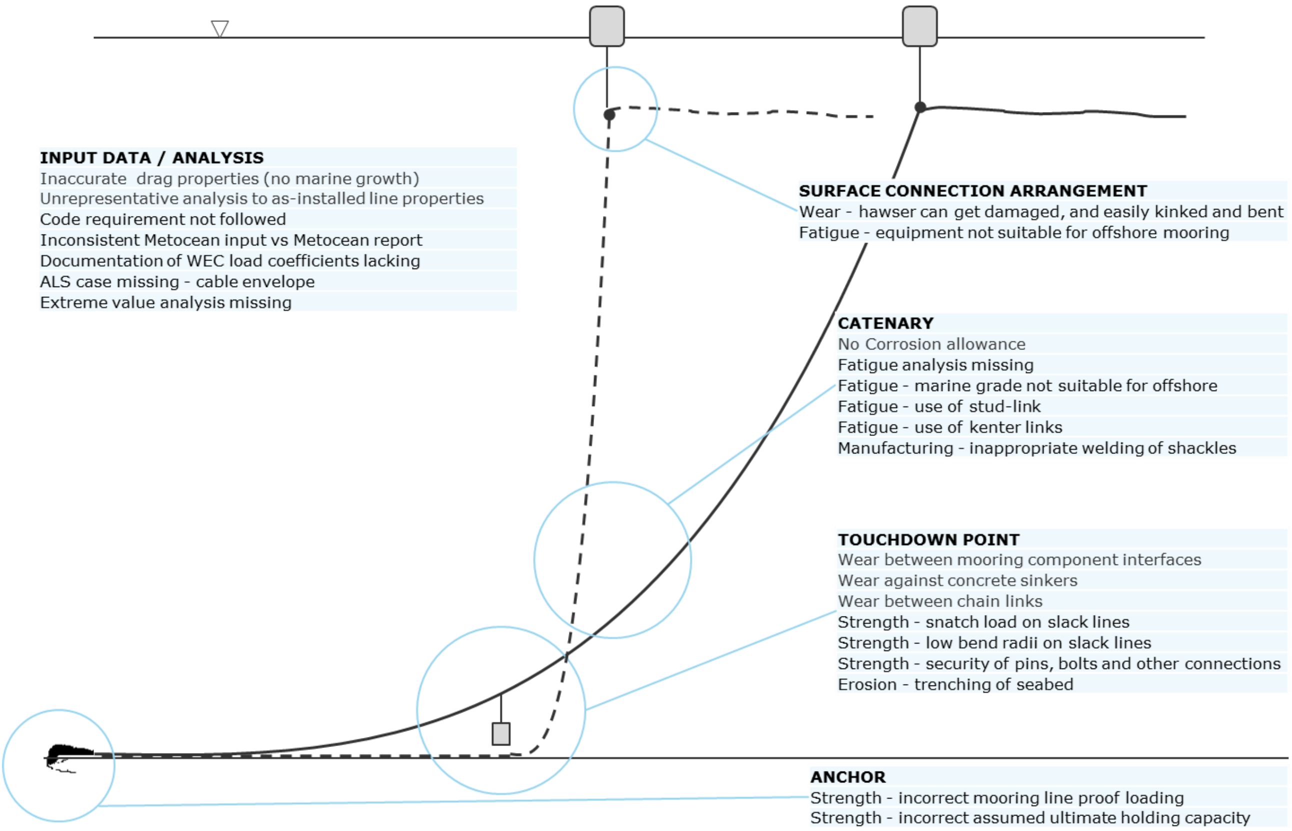


Figure 4-1 Failure mode long term integrity risk areas

5 REFERENCES

/1/ WETS final design report, Sound & Sea Technology engineering solutions 21 July 2014

/2/ WETS final design report Appendix A - Mooring Parametric Study, Sound & Sea Technology engineering solutions 21 July 2014

/3/ WETS installation final report, Sound & Sea Technology engineering solutions 30 September 2015

/4/ Wave power analysis for representative Hawaiian island sites, University of Hawaii September 2012

/5/ Geotechnical survey assessment WETS engineering services support, Sound & Sea Technology engineering solutions 21 July 2012

/6/ Memorandum Lifesaver in WETS Mooring A; Effect of Pretension on Motions, UPDATE TO INCLUDE SURVIVAL, Sound & Sea Technology engineering solutions 11 March 2016

/7/ Fred Olsen Wave Energy Test Site (FOWETS) Lifesaver Demonstration Final Mooring Design, Sound & Sea Technology engineering solutions 03 October 2016

/8/ Task 7D: WETS Deepwater Mooring Inspection, Sea Engineering January 2017

/9/ DRAFT REPORT: Wave Energy Test Site Comparison of Waverider Data and Sentinel V100 ADCP Data, Sea Engineering September 2015

/10/ Task 4C Wave Energy Test Site Sentinel V100 ADCP Data Analysis at 30m Site, Sea Engineering September 2016

/11/ IEC TS 62600-10:2015 Assessment of mooring systems for marine energy converters (MECs)

/12/ ISO19901-7:2013 Stationkeeping systems for floating offshore structures and mobile offshore units

/13/ DNVGL-OS-E301 Position mooring, July 2015

/14/ API-RP-2SK Design and analysis of stationkeeping systems for floating structures, 2005

/15/ ABS Rules for testing and certification of materials Part 2 Chapter 2, 2014

/16/ Oil and Gas UK, "Mooring Integrity Guidance", November 2008

/17/ Bruce Anchor Mfg Record Anchors June 2014 FF4-9-14-018

/18/ Bruce Anchor Mfg Record Anchors June 2014 FF4-9-14-019

/19/ Bruce Anchor Mfg Record Anchors June 2014 FF4-9-14-020

/20/ Bruce Anchor Mfg Record Anchors June 2014 FF4-9-14-021

/21/ Bruce Anchor Mfg Record Anchors June 2014 FF4-9-14-022

/22/ Bruce Anchor Mfg Record Anchors June 2014 FF4-9-14-023

/23/ Shackle SN2502031 NAZ13-159-1

/24/ Shackle SN2502031 NAZ13-159-2

/25/ Shackle SN2502031 NAZ13-159-3

/26/ Shackle SN2502031 NAZ13-159-4

/27/ Shackle SN2502031 NAZ13-159-5

/28/ Shackle SN2502031 NAZ13-159-6

/29/ Shackle SN2502031 NAZ13-159-7

/30/ Parts 3_4_5_12_7 QCL11736-1r0

A APPENDIX A – IEC TS 62600-10

Appendix A provides a description of the IEC TS 62600-10 safety factors for mooring tension and anchor holding capacity.

A.1 Consequence classification

The design approach using IEC TS 62600-10, requires the identification of consequence to assets of value in the event of mooring system failure considering the following categories:

- Person – injury or fatality
- Financial – loss of production, cost of repair, compensation
- Property – damage to device or third party property
- Environmental – possible injury, harassment, or death of ecosystems
- Societal – negative public perception

The evaluation of the consequence level should be determined through risk assessment (e.g. HAZID), with participation from the mooring designer and MEC developer/owner; an example of the format for conducting this HAZID is shown in Table A-1.

Table A-1 Consequence classification example

	Person		**Financial**		**Property**		**Environmental**		**Societal**		**Max**
Hazards	**Description**	**Consequence class**	**Description**	**Consequence class**	**Description**	**Consequence class**	**Description**	**Consequence class**	**Description**	**Consequence class**	**Consequence class**
Wave energy device issues											
Subsea infrastructure (e.g. pipeline)											
Local fish farm infrastructure											
Vessel traffic and navigable waterways											
Close-by archaeological sites											
Environmentally sensitive areas											

Each hazard is evaluated also considering mitigations in place and a score of 1 to 3 is allocated for each category:

- For consequence class 3, possible outcomes of mooring failure may include loss of human life, significant damage to marine environments, blockage of high traffic navigable waterways and substantial financial or third party property damage.
- For consequence class 2, possible outcomes of mooring failure may include serious injury, damage to marine environments, blockage of navigable waterways and financial or third party property damage.

- For consequence class 1, possible outcomes of mooring failure may include minor injury, minimal damage to marine environments, minimal blockage of navigable waterways and low financial or third party property damage.

Based on the overall consequence class a design factor (DF) is defined:

- Consequence class 3, DF = 1.5
- Consequence class 2, DF = 1.3
- Consequence class 1, DF = 1.0

A.2 Adjusted safety factor

The adjusted safety factor (ASF) approach is applied in IEC TS 62600-10. It states that:

$$ASF = DF * SF$$

where SF is the safety factor from ISO 19901-7.

Table A-2 Safety factors for ULS and ALS – Mooring tension

Condition	Analysis method	Safety factor (SF) ISO19901-7	Adjusted Safety factor (ASF) *
ULS – Intact condition	Dynamic	1.67	2.17
	Quasi-static	2.00	2.60
ALS – Redundancy check	Dynamic	1.25	1.63
	Quasi-static	1.43	1.86

* assuming consequence class 2 (to be confirmed by Sea Engineering)

Table A-3 Safety factors for ULS and ALS – Drag anchor holding capacity

Condition	Analysis method	Safety factor (SF) ISO19901-7	Adjusted Safety factor (ASF) *
ULS – Intact condition	Dynamic	1.50	1.95
	Quasi-static	N/A	N/A
ALS – Redundancy check	Dynamic	1.00	1.30
	Quasi-static	N/A	N/A

* assuming consequence class 2 (to be confirmed by Sea Engineering)

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