Structural report NSF#1

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Contents

1 Version control

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0.1	02-02-2023		In work version; all items are preliminary
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1.1	02-03-2023		For review; Remarks of first review incorporated

2 Introduction

2.1 Literature

[1] Report - Geological Ground Model, Wind Farm Site III Borssele, Wind Farm Zone Dutch Sector, North Sea, WOZ1500010, Issue 3, Fugro
[2] Metocean study for the Borssele Wind Farm Zone, 1210467-000-HYE-0012, 19 February 2015, final, Deltares
[3] 20150219_SDB_Deltares_Metocean study for the Borssele Wind Farm Zone Site III_Tables_F, Deltares
[4] API RP 2A WSD Designing and construction Fixed Offshore Platforms, including erratum and supplement 3
[5] ISO 19902:2007 Petroleum and natural gas industries – Fixed steel offshore structures
[6] Regulatory framework based on NS9415 and DNV-OS-E301, 20230113 - Regulatory Framework v0.2, Aqitec
[7] Design basis, 20230131_NSF1_design_basis_v1.0, Aqitec
[8] DNV-OS-C101
[9] Carter, M., and S.P. Bentley. (1991), Correlation of soil properties, Pentech Press, London
[10] Reese, Lymon C., Cox, William R., and Francis D. Koop. "Analysis of Laterally Loaded Piles in Sand." Paper presented at the Offshore Technology Conference, Houston, Texas, May 1974.
[11] Eco-anchor report 20072-20-RPT-01003-01, Enersea
[12] DNV-OS-E301
[13] 20221128_Calculation_Method_Description, Aqitec

2.2 Approach

A global analysis is performed using a lumped mass model. The model used is an internal software package developed by Aqitec and (at the moment of writing is being) independently evaluated by MARIN.

Load cases are extracted from a MetOcean report [2] and are evaluated according the Regulatory framework [6]. An initial set of expected critical (ULS) load cases is selected for which the design is first optimized. The optimized design is subsequently evaluated for all other load cases (ULS, ALS, FLS) according the Regulatory Framework [6]. The SLS and buoyancy are evaluated separately.

Note that the global analysis does not use any safety factors in its results. The results of the global analysis feed into a local analysis, where each component is evaluated based on the global analysis and the governing safety factors (load factor, material factor & corrosion allowance) .

2.3 Design

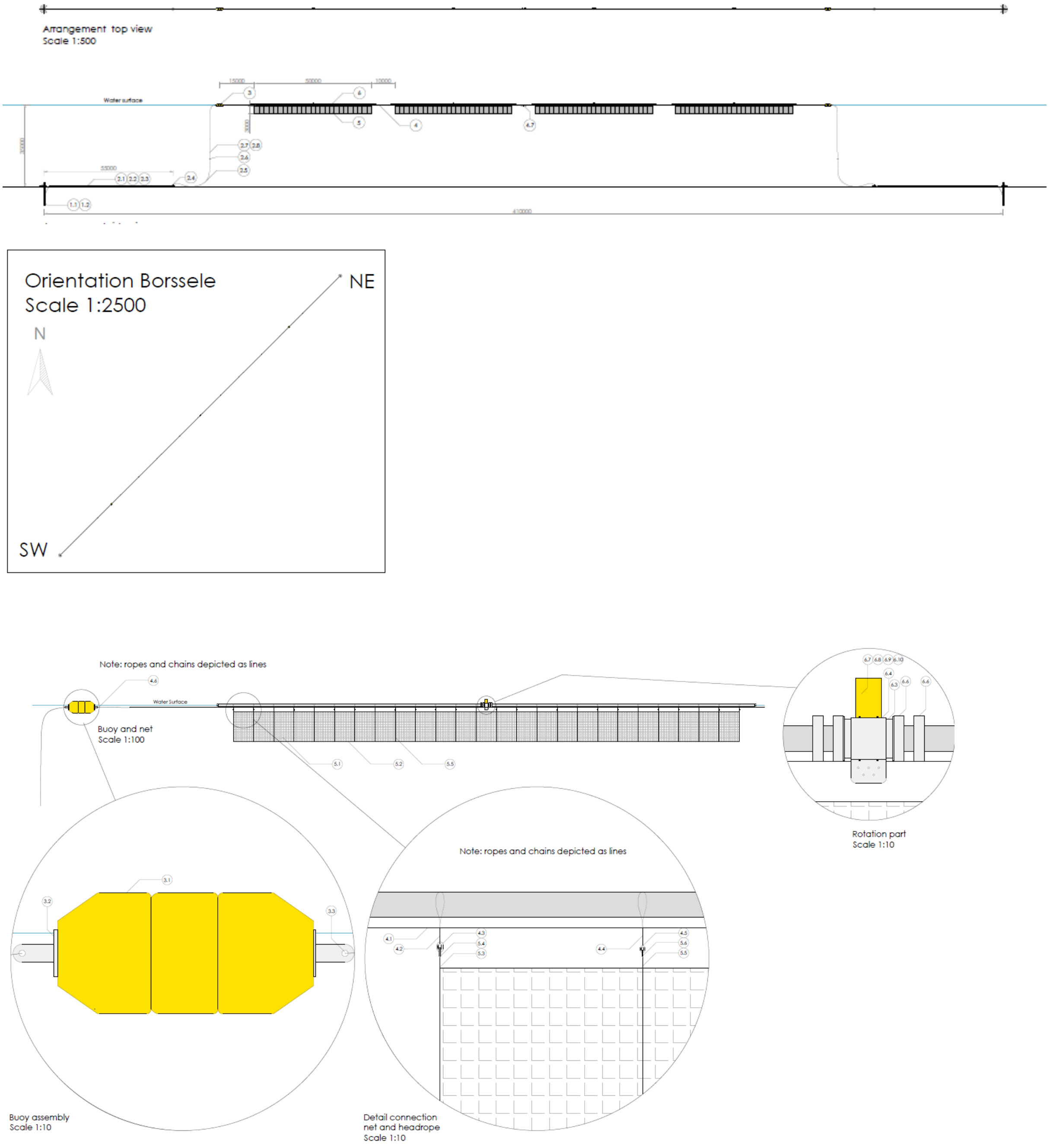

Figure 1: Design seaweed production system.

Table 1: Bill of materials

balloon	part number	part name	assys	amount per assy	Material*	Custom part
1	01-001	Pile anchor	2			
1.1	01-001-001	Weldment		1	Tbs	X
1.2	01-001-002	ECO structure		1	Tbs	X
2	01-002	Catenary assembly	2			
2.1	01-002-001	LTM anchor shackle (and spacers)		1	R3	
2.2	01-002-002	Stud link chain with enlarged end links		1	R3	
2.3	01-002-003	LTM Shackle		1	R3	
2.4	01-002-004	Concrete block		1	concrete	
2.5	01-002-006	Stud link chain with enlarged end links		1	R3	
2.6	01-002-007	Swivel shackle - Type A		1	R3	
2.7	01-002-008	12 Strand braided rope		1	LANKO®FORCE	
2.8	01-002-009	Thimble		2	Steel	
3	01-003	Buoy assembly	2			
3.1	01-003-001	Floaters		1 set	PE / PUR foam	
3.2	01-003-002	Weldment		1	Steel S355	X
3.3	01-003-003	Pin		2	Steel StE690	X
	01-004	Head rope assembly	1			
4.1	01-004-001	8 Strand braided rope		2	TIPTO®EIGHT	
4.2	01-004-002	Rope loop edge net		8	Nylon	
4.3	01-004-003	C-link 24mm		8	Steel SS	
4.4	01-004-004	Rope loop net		96	Nylon	
4.5	01-004-005	C-link 16mm		96	Steel SS	
4.6	01-004-006	Thimble		4	Steel	
4.7	01-004-007	Measurement / load link		1	Steel	
5	01-005	Net assembly	4			
5.1	01-005-001	Net		1	PP	
5.2	01-005-002	Sinker cable		1	Galvanized combination	
5.3	01-005-003	Vertical rope edge net		2	Nylon	
5.4	01-005-004	C-link 24mm		2	Steel SS	
5.5	01-005-005	Vertical rope net		24	Nylon	
5.6	01-005-006	C-link 16mm		24	Steel SS	
6	01-006	Pipe assembly	4			
6.1	01-006-001	Pipe Ø250		1	HDPE	
6.2	01-006-002	Pipe Ø280		1	HDPE	X
6.3	01-006-003	Wear sleeve		1	AISI316	X
6.4	01-006-004	Rotating element		1	UHMWPE	X
6.5	01-006-005	Brackets		2	AISI316	X
6.6	01-006-006	Clamping flange pipe		4	HDPE	X
6.7	01-006-007	GNSS unit		1		
6.8	01-006-008	Camera unit		1		
6.9	01-006-009	Radar reflector		1		
6.10	01-006-010	Top light		1		

* For all materials: equivalent alternatives can be used

The design includes three structural parts that have a custom design; pile anchor, weldment buoy and the pipe rotation part. Local analyses of these parts is included in chapter 8.

2.4 Load factors

The regulatory framework [6] includes load factors and material factors to be used in analyses. The load factor for use in ULS dynamic analysis is 1.3 for the environmental loads, however according to DNV-OS-C101 [8] may be reduced to 1.15.

Chapter 2 Section 1 states four load categories and two combinations of design loads. The combination of environmental loads and permanent (hydrostatic and pre-tension) loads are relevant for the ULS of the seaweed production system. The environmental loads are the dominant load effect, therefore load combination b) is considered. The calculation is applying the same load factor for both environmental and permanent loads.

DNV-OS-C101 includes a reduction for the load factor for load combination b): " Based on a safety assessment considering the risk for both human life and the environment, the load factor γ for environmental loads may be reduced to 1.15 in combination b) if the structure is unmanned during extreme environmental conditions."

The risk for human life and environment is considered to be very low. It is not possible for humans to be present on the seaweed production system. Operations will always be executed on a vessel, where the seaweed production system is handled by winches, cranes or other mechanical devices. Depending on the vessel work will only be performed during very low or low sea states, with maximum wave height up to 1.25 meter. During extreme weather no humans will be present in the aquaculture site and neighbouring wind farm infrastructure.

The Design Basis for the NSF#1 includes a risk assessment where the risk associated with loss of equipment is assessed. To minimize the risk of loss of components (and subsequently flotsam that poses risk to vessels, infrastructure and the environment) is mitigated using controls divided in three groups:

- Component level; where the size of the components is minimized (nets, pipes) and heavy (steel) buoys are substituted for lightweight plastic variants.
- Adoption of inherent safety design philosophy; components fail in a specific order where the created ALS (weathervaning, reduced buoyancy, nets sunk to seabed) results in lowering of loads on the remainder of the components.
- Operational risk controls; quality management strategy, on-site and remote monitoring and intervention (cleaning, maintenance and system incident interventions).

Based on the risk assessment the identified risks (also for humans and environment) can be managed. In compliance with DNV-OS-C101 Chapter 2 Section 1 the load factor of 1.15 is applied.

3 Load cases

3.1 ULS

3.1.1 Input from Regulatory Framework and Design basis

According the Regulatory Framework [6] the following combinations of load cases (see table below) need to be evaluated, however combination #3 (Ice) does not apply to this location according the Design basis [7].

Nearly all components of the seaweed system are below water level, especially during an extreme sea state. The effect of wind on the components partly above water (buoys) is very small compared to other loads and for this reason the wind is neglected in all the load cases.

Based on modelling experience with other systems in the North Sea, combination #1 will be leading. For this reason all load cases for combination #1 will be evaluated first. Subsequently the most critical load case is evaluated for combination #2.

Even though not necessary according the Regulatory Framework some load cases with minimum and maximum sea level are evaluated as well. Effect of wave period is also investigated in the load cases.

Table 2: Return period (in years) of combined load cases according the Regulatory Framework [6]

	Wind	Waves	Current	Ice	Sea level
Combination #1	50	50	10		-
Combination #2	10	10	50		-
Combination #3	10	10	10	50	-

3.1.2 Input from MetOcean studies

Extreme sea state (wave) and extreme current conditions have been evaluated by Deltares in a 2015 MetOcean study [2]. In the appendix of the MetOcean report an Excel sheet is available [3].

Extreme Sea States are extracted from [3] by using the values for maximum still water level to be conservative (values at minimum still water level are lower). Corresponding average peak wave period from [3] is used in the load cases. Extreme currents are also extracted from [3] and are the currents at 100% total depth (at the surface).

The MetOcean report states that the wave height, wave period and current velocities are accurate up to 1 digit after the comma and it is advised to round the data. We will use both digits after the comma and acknowledge that this gives a misleading accuracy.

3.1.3 Water level

Table 3: Water level

	Depth [m]	Source
50y extreme maximum	35.0 + 3.1 = 38.1	MetOcean Report [2]
Nominal	35.0	Design basis [7]
50y extreme minimum	35.0 – 2.2 = 32.8	MetOcean Report [2]

3.1.4 Evaluating load cases

The MetOcean data differentiates between 12 directions; this results in 144 individual combinations of wave and current directions. Due to the double-mirror symmetry of the seaweed system 4 combinations of directions are the same and only the combination with the highest wave and/or current needs to be considered for further analysis. Data for co-occurrence of waves and current is available, however is not used to exclude any load cases.

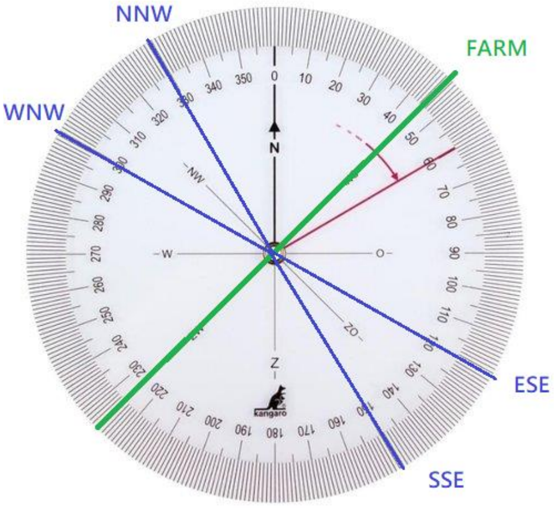

Figure 2: Example of 4 directions that are the same during evaluation due to mirror symmetry.

The coordinate systems are not the same in our model and in the MetOcean data, for this reason we need to transform the data set using the differences indicated in the table below. Additionally the wave direction is preferably kept between 0-180 degrees in the model.

Table 4: Directions data

	MetOcean data	Model
0 degrees points to	North	Perpendicular to system
Wave direction given as	Coming from direction	Coming from direction
Current direction given as	Going towards direction	Coming from direction

The table below shows all 144 load combinations and uses the following color coding.

- Expected critical load cases. These load cases are used for first iterations and optimizing the dimensions of the farm. Used as input for the simulations.
- Secondary critical load cases. These are used to check the optimized design and are used as input for the simulations.
- Identified main load case(s) for this direction. However similar (adjacent) load cases have higher current velocity and/or wave height. These load cases are not used as input for the simulations.
- Not a main load case for this direction. Other load cases have larger wave height and/or current velocity. These load cases are not used as input for the simulations.

Table 5: Extreme current and maximum wave height from MetOcean report and corresponding directions used in the model. Colour coding as stated above.

Base		Opposite		Base mirrored		Opposite mirrored		Model		LC
Current 10y/50y [m/s]	Waves 10y/50y [m]	Current 10y/50y [m/s]	Waves 10y/50y [m]	Current 10y/50y [m/s]	Waves 10y/50y [m]	Current 10y/50y [m/s]	Waves 10y/50y [m]	Current	Waves	
N (0) **1.00/1.04**	N (0) 10.85/12.66	S (180) 0.97/1.04	S (180) 8.59 / 9.63	E (90) 0.86/0.92	E (90) 6.10 / 7.26	W (270) 0.8/0.86	***W (270)*** ***12.17 / 14.12***	*225* *(315)*	*45* *(135)*	*26*
N (0) **1.00/1.04**	NNE (30) 8.31 / 9.97	S (180) 0.97/1.04	SSW (210) 11.35 / 12.70	E (90) 0.86/0.92	ENE (60) 7.39 / 8.79	W (270) 0.8/0.86	***WSW (240)*** **12.22 / 13.95**	*225* *(315)*	*75* *(105)*	
N (0) **1.00/1.04**	ENE (60) 7.39 / 8.79	S (180) 0.97/1.04	***WSW (240)*** **12.22 / 13.95**	E (90) 0.86/0.92	NNE (30) 8.31 / 9.97	W (270) 0.8/0.86	SSW (210) 11.35 / 12.70	*225* *(315)*	105 (75)	
N (0) **1.00/1.04**	E (90) 6.10 / 7.26	S (180) 0.97/1.04	***W (270)*** ***12.17 / 14.12***	E (90) 0.86/0.92	N (0) 10.85/12.66	W (270) 0.8/0.86	S (180) 8.59 / 9.63	*225* *(315)*	135 (45)	30
N (0) **1.00/1.04**	ESE (120) 5.60 / 6.51	S (180) 0.97/1.04	WNW (300) 11.21 / 12.70	E (90) 0.86/0.92	***NNW (330)*** ***12.45 / 14.69***	W (270) 0.8/0.86	SSE (150) 6.52 / 7.80	*225* *(315)*	165 (15)	

N (0) **1.00/1.04**	SSE (150) 6.52 / 7.80	S (180) 0.97/1.04	***NNW (330)*** ***12.45 / 14.69***	E (90) 0.86/0.92	WNW (300) 11.21 / 12.70	W (270) 0.8/0.86	ESE (120) 5.60 / 6.51	45 (135)	15 (165)	27
N (0) **1.00/1.04**	S (180) 8.59 / 9.63	S (180) 0.97/1.04	N (0) 10.85/12.66	E (90) 0.86/0.92	***W (270)*** ***12.17 / 14.12***	W (270) 0.8/0.86	E (90) 6.10 / 7.26	45 (135)	45 (135)	
N (0) **1.00/1.04**	SSW (210) 11.35 / 12.70	S (180) 0.97/1.04	NNE (30) 8.31 / 9.97	E (90) 0.86/0.92	***WSW (240)*** **12.22 / 13.95**	W (270) 0.8/0.86	ENE (60) 7.39 / 8.79	45 (135)	75 (105)	
N (0) **1.00/1.04**	***WSW (240)*** **12.22 / 13.95**	S (180) 0.97/1.04	ENE (60) 7.39 / 8.79	E (90) 0.86/0.92	SSW (210) 11.35 / 12.70	W (270) 0.8/0.86	NNE (30) 8.31 / 9.97	45 (135)	105 (75)	15
N (0) **1.00/1.04**	***W (270)*** ***12.17 / 14.12***	S (180) 0.97/1.04	E (90) 6.10 / 7.26	E (90) 0.86/0.92	S (180) 8.59 / 9.63	W (270) 0.8/0.86	N (0) 10.85/12.66	45 (135)	135 (45)	1
N (0) **1.00/1.04**	WNW (300) 11.21 / 12.70	S (180) 0.97/1.04	ESE (120) 5.60 / 6.51	E (90) 0.86/0.92	SSE (150) 6.52 / 7.80	W (270) 0.8/0.86	***NNW (330)*** ***12.45 / 14.69***	*45* *(135)*	*165* *(15)*	*16*
N (0) **1.00/1.04**	***NNW (330)*** ***12.45 / 14.69***	S (180) 0.97/1.04	SSE (150) 6.52 / 7.80	E (90) 0.86/0.92	ESE (120) 5.60 / 6.51	W (270) 0.8/0.86	WNW (300) 11.21 / 12.70	225 (315)	15 (165)	2
NNW (330) **0.72/0.78**	N (0) 10.85/12.66	SSE (150) 0.67/0.72	S (180) 8.59 / 9.63	WNW (300) 0.67/0.73	E (90) 6.10 / 7.26	ESE (120) 0.64/0.68	***W (270)*** ***12.17 / 14.12***	*195* *(345)*	*45* *(135)*	*31*
NNW (330) **0.72/0.78**	NNE (30) 8.31 / 9.97	SSE (150) 0.67/0.72	SSW (210) 11.35 / 12.70	WNW (300) 0.67/0.73	ENE (60) 7.39 / 8.79	ESE (120) 0.64/0.68	***WSW (240)*** **12.22 / 13.95**	*195* *(345)*	*75* *(105)*	
NNW (330) **0.72/0.78**	ENE (60) 7.39 / 8.79	SSE (150) 0.67/0.72	***WSW (240)*** **12.22 / 13.95**	WNW (300) 0.67/0.73	NNE (30) 8.31 / 9.97	ESE (120) 0.64/0.68	SSW (210) 11.35 / 12.70	195 (345)	105 (75)	
NNW (330) **0.72/0.78**	E (90) 6.10 / 7.26	SSE (150) 0.67/0.72	***W (270)*** ***12.17 / 14.12***	WNW (300) 0.67/0.73	N (0) 10.85/12.66	ESE (120) 0.64/0.68	S (180) 8.59 / 9.63	195 (345)	135 (45)	3
NNW (330) **0.72/0.78**	ESE (120) 5.60 / 6.51	SSE (150) 0.67/0.72	WNW (300) 11.21 / 12.70	WNW (300) 0.67/0.73	***NNW (330)*** ***12.45 / 14.69***	ESE (120) 0.64/0.68	SSE (150) 6.52 / 7.80	195 (345)	165 (15)	
NNW (330) **0.72/0.78**	SSE (150) 6.52 / 7.80	SSE (150) 0.67/0.72	***NNW (330)*** ***12.45 / 14.69***	WNW (300) 0.67/0.73	WNW (300) 11.21 / 12.70	ESE (120) 0.64/0.68	ESE (120) 5.60 / 6.51	15 (165)	15 (165)	32
NNW (330) **0.72/0.78**	S (180) 8.59 / 9.63	SSE (150) 0.67/0.72	N (0) 10.85/12.66	WNW (300) 0.67/0.73	***W (270)*** ***12.17 / 14.12***	ESE (120) 0.64/0.68	E (90) 6.10 / 7.26	15 (165)	45 (135)	
NNW (330) **0.72/0.78**	SSW (210) 11.35 / 12.70	SSE (150) 0.67/0.72	NNE (30) 8.31 / 9.97	WNW (300) 0.67/0.73	***WSW (240)*** **12.22 / 13.95**	ESE (120) 0.64/0.68	ENE (60) 7.39 / 8.79	15 (165)	75 (105)	33
NNW (330) **0.72/0.78**	***WSW (240)*** **12.22 / 13.95**	SSE (150) 0.67/0.72	ENE (60) 7.39 / 8.79	WNW (300) 0.67/0.73	SSW (210) 11.35 / 12.70	ESE (120) 0.64/0.68	NNE (30) 8.31 / 9.97	15 (165)	105 (75)	
NNW (330) **0.72/0.78**	***W (270)*** ***12.17 / 14.12***	SSE (150) 0.67/0.72	E (90) 6.10 / 7.26	WNW (300) 0.67/0.73	S (180) 8.59 / 9.63	ESE (120) 0.64/0.68	N (0) 10.85/12.66	15 (165)	135 (45)	34
NNW (330) **0.72/0.78**	WNW (300) 11.21 / 12.70	SSE (150) 0.67/0.72	ESE (120) 5.60 / 6.51	WNW (300) 0.67/0.73	SSE (150) 6.52 / 7.80	ESE (120) 0.64/0.68	***NNW (330)*** ***12.45 / 14.69***	*15* (165)	*165* *(15)*	
NNW (330) **0.72/0.78**	***NNW (330)*** ***12.45 / 14.69***	SSE (150) 0.67/0.72	SSE (150) 6.52 / 7.80	WNW (300) 0.67/0.73	ESE (120) 5.60 / 6.51	ESE (120) 0.64/0.68	WNW (300) 11.21 / 12.70	195 (345)	15 (165)	28
WSW (240) 1.17/1.27	N (0) 10.85/12.66	ENE (60) 1.43/1.54	S (180) 8.59 / 9.63	SSW (210) 1.52/1.59	E (90) 6.10 / 7.26	**NNE (30)** **1.56/1.66**	***W (270)*** ***12.17 / 14.12***	*105* *(75)*	*45* *(135)*	*4*
WSW (240) 1.17/1.27	NNE (30) 8.31 / 9.97	ENE (60) 1.43/1.54	SSW (210) 11.35 / 12.70	SSW (210) 1.52/1.59	ENE (60) 7.39 / 8.79	**NNE (30)** **1.56/1.66**	***WSW (240)*** **12.22 / 13.95**	*105* *(75)*	*75* *(105)*	*5*
WSW (240) 1.17/1.27	ENE (60) 7.39 / 8.79	ENE (60) 1.43/1.54	***WSW (240)*** **12.22 / 13.95**	SSW (210) 1.52/1.59	NNE (30) 8.31 / 9.97	**NNE (30)** **1.56/1.66**	SSW (210) 11.35 / 12.70	*105* *(75)*	*105* *(75)*	*13*
WSW (240) 1.17/1.27	E (90) 6.10 / 7.26	ENE (60) 1.43/1.54	***W (270)*** ***12.17 / 14.12***	SSW (210) 1.52/1.59	N (0) 10.85/12.66	**NNE (30)** **1.56/1.66**	S (180) 8.59 / 9.63	105 (75)	135 (45)	6
WSW (240) 1.17/1.27	ESE (120) 5.60 / 6.51	ENE (60) 1.43/1.54	WNW (300) 11.21 / 12.70	SSW (210) 1.52/1.59	***NNW (330)*** ***12.45 / 14.69***	**NNE (30)** **1.56/1.66**	SSE (150) 6.52 / 7.80	105 (75)	165 (15)	35
WSW (240) 1.17/1.27	SSE (150) 6.52 / 7.80	ENE (60) 1.43/1.54	***NNW (330)*** ***12.45 / 14.69***	SSW (210) 1.52/1.59	WNW (300) 11.21 / 12.70	**NNE (30)** **1.56/1.66**	ESE (120) 5.60 / 6.51	285 (255)	15 (165)	14
WSW (240) 1.17/1.27	S (180) 8.59 / 9.63	ENE (60) 1.43/1.54	N (0) 10.85/12.66	SSW (210) 1.52/1.59	***W (270)*** ***12.17 / 14.12***	**NNE (30)** **1.56/1.66**	E (90) 6.10 / 7.26	285 (255)	45 (135)	7
WSW (240) 1.17/1.27	SSW (210) 11.35 / 12.70	ENE (60) 1.43/1.54	NNE (30) 8.31 / 9.97	SSW (210) 1.52/1.59	***WSW (240)*** **12.22 / 13.95**	**NNE (30)** **1.56/1.66**	ENE (60) 7.39 / 8.79	285 (255)	75 (105)	8
WSW (240) 1.17/1.27	***WSW (240)*** **12.22 / 13.95**	ENE (60) 1.43/1.54	ENE (60) 7.39 / 8.79	SSW (210) 1.52/1.59	SSW (210) 11.35 / 12.70	**NNE (30)** **1.56/1.66**	NNE (30) 8.31 / 9.97	285 (255)	105 (75)	9
WSW (240) 1.17/1.27	***W (270)*** ***12.17 / 14.12***	ENE (60) 1.43/1.54	E (90) 6.10 / 7.26	SSW (210) 1.52/1.59	S (180) 8.59 / 9.63	**NNE (30)** **1.56/1.66**	N (0) 10.85/12.66	285 (255)	135 (45)	10
WSW (240) 1.17/1.27	WNW (300) 11.21 / 12.70	ENE (60) 1.43/1.54	ESE (120) 5.60 / 6.51	SSW (210) 1.52/1.59	SSE (150) 6.52 / 7.80	**NNE (30)** **1.56/1.66**	***NNW (330)*** ***12.45 / 14.69***	285 *(255)*	*165* *(15)*	*29*
WSW (240) 1.17/1.27	***NNW (330)*** ***12.45 / 14.69***	ENE (60) 1.43/1.54	SSE (150) 6.52 / 7.80	SSW (210) 1.52/1.59	ESE (120) 5.60 / 6.51	**NNE (30)** **1.56/1.66**	WNW (300) 11.21 / 12.70	105 (75)	15 (165)	

Note that the rightmost column indicates the corresponding load case if applicable, due to the iterative design process the numbering is in order of evaluating. The red load cases have been used during optimization of the seaweed system design, once the design satisfies the requirements for these load cases, the yellow load cases are simulated. The white and grey load cases are not used as model input as they are either not the leading load case for the combination of wave and current direction (white) or (grey) load cases with a very minor change in direction and higher wave/current are model input. Due to the lower environmental loads on the system in the white and grey load cases, these load cases are very unlikely to result in higher loads in the system.

3.1.5 Model input

The table below shows the load cases that are used as model input. Besides the load cases as stated in the previous section, additional load cases are added to evaluate sensitivity. Load case #2 has the highest anchor loads and is selected as the main load case for sensitivity studies.

- #1 - #10
    - Expected critical load cases. Load case #2 resulted in the highest loads on the system.
- #11 - #12
    - Expected critical load cases. Perpendicular and parallel direction compared to farm are used instead of middle of quadrant in MetOcean report.
- #13-#16, #26-#35
    - Secondary critical load cases
- #17-#20
    - Evaluation of the wave period sensitivity. Load case #2 and #7 are used as base
- #21-#23
    - Evaluation of 50y current / 10y waves, which is expected to result in lower loads on the system. Based on load case #2, #7 and #8.
- #24-#25
    - Evaluation of the water depth sensitivity. Maximum (#24) and minimum (#25) water depth are evaluated based on load case #2

Notes on the bottom of the table are explained in chapter ‘global analysis’.

Table 6: Load cases used as model input

	Current 10y/50y [m/s]	Waves 10y/50y [m]	Model input Current [m/s]	Model input Current direction [deg]	Model input Maximum wave height [m]	Model input Wave direction [deg]	Peak Wave Period [s]
#1	N (0) 1.00/1.04	*W (270)* *12.17 / 14.12*	1.00	45 (135)	14.12	135 (45)	10.74
#2	N (0) 1.00/1.04	*NNW (330)* *12.45 / 14.69*	1.00	225 (315)	14.69	15 (165)	12.5
#3	SSE (150) 0.67/0.72	*W (270)* *12.17 / 14.12*	0.67	195 (345)	14.12	135 (45)	10.74
#4	NNE (30) 1.56/1.66	*W (270)* *12.17 / 14.12*	*1.56*	*105* *(75)*	*14.12*	*45* *(135)*	*10.74*
#5	NNE (30) 1.56/1.66	*WSW (240)* 12.22 / 13.95	*1.56*	*105* *(75)*	*13.95*	*75* *(105)*	*10.45*
#6	ENE (60) 1.43/1.54	*W (270)* *12.17 / 14.12*	1.43[4]	105 (75)	14.12	135 (45)	10.74
#7	SSW (210) 1.52/1.59	*W (270)* *12.17 / 14.12*	1.52[4]	285 (255)	14.12	45 (135)	10.74
#8	SSW (210) 1.52/1.59	*WSW (240)* 12.22 / 13.95	1.52[4]	285 (255)	13.95	75 (105)	10.45
#9	WSW (240) 1.17/1.27	*WSW (240)* 12.22 / 13.95	1.17	285 (255)	13.95	105 (75)	10.45
#10	WSW (240) 1.17/1.27	*W (270)* *12.17 / 14.12*	1.17	285 (255)	14.12	135 (45)	10.74
#11	In-line		1.56	90	13.95	90	*10.45*
#12	Perpendicular		0.67	0	14.69	0	*12.5*
Identified secondary load cases							
#13	NNE (30) 1.56/1.66	SSW (210) 11.35 / 12.70	1.56	*105* *(75)*	*12.70*	*105* *(75)*	*9.87*
#14	ENE (60) 1.43/1.54	NNW (330) 12.45 / 14.69	1.43[4]	285 (255)	14.69	15 (165)	12.5
#15	N (0)	*WSW (240)*	1.00	45	13.95	105	*10.45*

	1.00/1.04	12.22 / 13.95		(135)		(75)	
#16	N (0) 1.00/1.04	WNW (300) 11.21 / 12.70	1.00	*45* (135)	12.7	*165* *(15)*	*10.50*
Wave length sensitivity – based on #2, #7							
#17	N (0) 1.00/1.04	*NNW (330)* *12.45 / 14.69*	1.00	225 (315)	14.7	15 (165)	11 (11.77)
#18	N (0) 1.00/1.04	*NNW (330)* *12.45 / 14.69*	1.00	225 (315)	14.7	15 (165)	*(12.89)* *14*
#19	SSW (210) 1.52/1.59	*W (270)* *12.17 / 14.12*	1.52[4]	285 (255)	14.12	45 (135)	(10.66) 9.25
#20	SSW (210) 1.52/1.59	*W (270)* *12.17 / 14.12*	1.52[4]	285 (255)	14.12	45 (135)	*(10.96)* *12.25*
50y / 10y – based on #2, #7, #8							
#21	N (0) 1.00/1.04	*NNW (330)* *12.45 / 14.69*	1.04[1]	225 (315)	12.45	15 (165)	*11.51*
#22	SSW (210) 1.52/1.59	*W (270)* *12.17 / 14.12*	1.59[4]	285 (255)	12.17	45 (135)	*10.07*
#23	SSW (210) 1.52/1.59	*WSW (240)* 12.22 / 13.95	1.59[4]	285 (255)	12.22	75 (105)	*9.71*
Depth sensitivity – based on #2							
#24	N (0) 1.00/1.04	*NNW (330)* *12.45 / 14.69*	1.00	225 (315)	14.69	15 (165)	12.5
#25	N (0) 1.00/1.04	*NNW (330)* *12.45 / 14.69*	1.00	225 (315)	14.69	15 (165)	12.5
Additional secondary load cases							
#26	W (270) 0.8/0.86	***W (270)*** ***12.17 / 14.12***	0.86[1]	*225* *(315)*	14.12	*45* *(135)*	*10.74*
#27	S (180) 0.97/1.04	*NNW (330)* *12.45 / 14.69*	0.97[1]	45 (135)	14.69	15 (165)	*12.5*
#28	NNW (330) 0.72/0.78	*NNW (330)* *12.45 / 14.69*	0.72[2]	195 (345)	14.69	15 (165)	12.5
#29	NNE (30) 1.56/1.66	*NNW (330)* *12.45 / 14.69*	1.56	285 *(255)*	14.69	*165* *(15)*	12.5
#30	S (180) 0.97/1.04	*W (270)* *12.17 / 14.12*	0.97[1]	*225* *(315)*	14.69	135 (45)	12.5
#31	ESE (120) 0.64/0.68	*W (270)* *12.17 / 14.12*	0.64[2]	*195* *(345)*	14.12	*45* *(135)*	10.74
#32	SSE (150) 0.67/0.72	*NNW (330)* *12.45 / 14.69*	0.67[3]	15 (165)	14.69	15 (165)	12.5
#33	WNW (300) 0.67/0.73	*WSW (240)* 12.22 / 13.95	0.67[3]	15 (165)	13.95	75 (105)	10.45
#34	NNW (330) 0.72/0.78	*W (270)* *12.17 / 14.12*	0.72	15 (165)	14.12	135 (45)	10.74
#35	SSW (210) 1.52/1.59	*NNW (330)* *12.45 / 14.69*	1.52[4]	105 (75)	14.69	165 (15)	12.5
Reduced parallel seaweed drag coefficient – based on #27							
#36	S (180) 0.97/1.04	*NNW (330)* *12.45 / 14.69*	0.97	45 (135)	14.69	15 (165)	*12.5*

1) Uses 1.00 m/s current during pre-ramp to stabilize to reduce computing time
2) Uses 0.67 m/s current during pre-ramp to stabilize to reduce computing time
3) Uses 0.72 m/s current during pre-ramp to stabilize to reduce computing time
4) Uses 1.56 m/s current during pre-ramp to stabilize to reduce computing time

3.2 ALS

Two points of failure are considered in the Accidental Load State.

- ALS#1 – Failure between the net and the buoy (Considered system indicated inside orange square)
- ALS#2 – Failure in the center of the system (Considered system indicated inside green square)

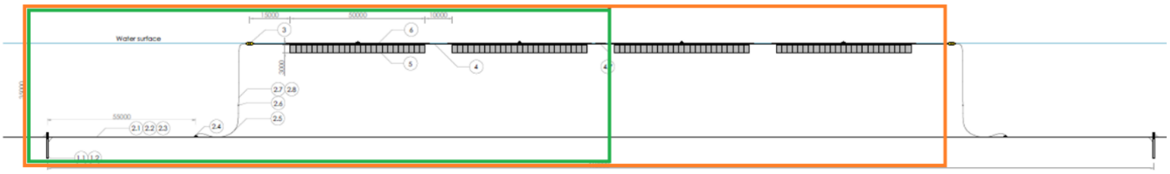

Figure 3 : Indication of ALS#1 (orange) and ALS#2 (green)

After initial failure partial systems are single anchored and expected to weathervane (align with current), when the current direction switches the system is not fully tensioned, therefore the loads on the system during this time is expected to be lower and this situation is not simulated.

The following load cases are used as input for simulations:

Table 7: ALS load cases for simulation

Load cases	ALS	Model input Current [m/s]	Model input Current direction [deg]	Model input Maximum wave height [m]	Model input Wave direction [deg]	Peak Wave Period [s]
201	ALS#1 Failure near the buoy	1.42[1]	90	9.71[2]	90	8.84[3]
202					45	
203					0	
204					315	
205					270	
206	ALS#2 Failure in center of system		90		90	
207					45	
208					0	
209					315	
210					270	

1) Highest directional extreme surface current velocity with a return period of 1 year [3]
2) Highest wave height for extreme sea state with return period of 1 year [3]
3) Peak wave period corresponding to selected wave height [3]

The highest (directional) current and (directional) wave height is used in these load cases, lower wave heights and currents are not considered as they are expected to result in lower loads on the system. Return period of 1 year is selected as prescribed in [6].

The ALS model uses the same properties as specified for the ULS.

3.3 FLS

A Normal Sea State is available from the MetOcean report [2], which provides significant wave height, wave period and duration divided into 24 bins. To calculate the amount of cycles we will assume the significant wave height applies each wave period. For the wave period a typical range is given in [2], the center of this range is used in this analysis.

Table 8: Load spectrum (Source: [2])

Bin No.	Hs	duration %	T	waves/y
[-]	[m]	[-]	[s]	[n/y]
1	0.6	19.42	3.2	1913841
2	0.8	10.99	3.55	976283
3	0.9	11.84	3.8	982595
4	1	11.15	4.1	857625
5	1.2	9.96	4.45	705839
6	1.4	8.58	4.8	563706
7	1.6	6.9	5.15	422521
8	**1.8**	**5.59**	**5.5**	**320520**
9	2.1	4.38	5.85	236116
10	2.3	3.33	6.2	169379
11	2.6	2.55	6.6	121844
12	2.9	1.78	6.9	81354
13	3.2	1.31	7.2	57378
14	3.4	0.89	7.45	37674
15	3.7	0.62	7.8	25067
16	**4**	**0.31**	**8.1**	**12069**
17	4.3	0.18	8.35	6798
18	4.5	0.1	8.6	3667
19	4.7	0.07	8.7	2537
20	4.9	0.02	9	701
21	5.2	0.02	9.3	678
22	5.3	0.01	9.3	339
23	5.9	0.01	9.85	320
24	**6.6**	**0**	**10.45**	**0**

The wave height needs to be converted to a stress range; this is done by simulating the load cases of 3 bins (indicated in bold in the table above) and interpolating between them. A current is also applied to the load cases, as otherwise the system is not in tension and the loads will be underestimated. A typical current of 1 m/s is applied, which corresponds to a typical daily peak current.

For the direction of wave and current the two governing combinations of directions are selected. Current is very stable and is mainly aligned with the system. Waves have two governing directions, either aligned or (near) perpendicular to the system. Simulated load cases are shown in the table below.

Table 9: Load cases used as model input for FLS

	Current 10y/50y	Waves 10y/50y	Model input Current	Model input Current direction	Model input Maximum wave height	Model input Wave direction	Peak Wave Period
	[m/s]	[m]	[m/s]	[deg]	[m]	[deg]	[s]
#101	In-line 1.00	*In-line* *4m*	1.00	90	4	*90*	*8.1*
#102	In-line 1.00	*Perpendicular* *4m*	1.00	90	4	*0*	*8.1*
#103	In-line 1.00	*Perpendicular* *1.8m*	1.00	90	1.8	*0*	*5.5*
#104	In-line 1.00	*Perpendicular* *6.6m*	1.00	90	6.6	*0*	*10.45*
#105	In-line 1.00	*In-line* *1.8m*	1.00	90	1.8	*90*	*5.5*
#106	In-line 1.00	*In-line* *6.6m*	1.00	90	6.6	*90*	*10.45*

The highest resulting load range for each combination of directions is used in further analysis, this step is performed in the results.

Each component has its own properties, which is shown in the table below. Stress is conservatively calculated by reducing the cross sectional area of the chain according the corrosion allowance and design life.

Table 10: Life components

Part number	Part name	Design life[1]	Location	Corrosion allowance[2]	Design Fatigue Factor[3]
01-002-001	LTM anchor shackle*	25y	Bottom	0.4mm/y	3
01-002-002	**Anchoring chain**	**25y**	**Bottom**	**0.4mm/y**	**3**
01-002-003	LTM shackle*	25y	Bottom	0.4mm/y	3
01-002-006	**Mooring chain**	**10y**	**Catenary**	**0.3mm/y**	**3**
01-002-007	LTM Swivel shackle*	10y	Catenary	0.3mm/y	3
01-002-008	**Mooring rope**	**10y**	**Catenary**	**-**	**3**
01-003-001	**Buoy**	**10y**	**Splash zone**	**0.4mm/y**	**3**
01-004-001	**Headrope**	**10y**	**Splash zone**	**-**	**3**
*Long term mooring (LTM) D-shackles, H-shackles and swivels are designed to have superior fatigue strength compared to the chain and can be excluded from the analysis [6].					

1) Source: [7]
2) Source [6], based on regular inspection carried out by ROV.
3) Source [6], based on non-accessible areas and/or in the splash zone.

Fatigue damage is calculated using the linear damage theory (Palmgren-Miner). Fatigue curve parameters are taken from the DNV standard [12]. Calculations are performed according this standard, where steel chains use a formula based on stress range and fiber ropes use a formula based on ratio between tension range to characteristic strength.

Table 11: Fatigue curve parameters according [12]

	ad	m
Stud chain	1.2*10^11	3.0
Fibre rope*	0.259	13.46

*Parameters are based on polyester rope as other parameters were not available.

4 Model components

The lumped mass model is a representation of the actual seaweed system. Especially the nets are simplified to obtain a practical model in terms of computing time. Used values for the parameters of each item are given in the table below with some remarks to explain choices made. Values are based on DNV standards (Cd, Ca and Cf), supplier data (E-mod, weight, MBL, relative density) and MetOcean reports (fouling), parameters for which values are not present are estimated based on internal research. Additional detail on the model itself is described in [13].

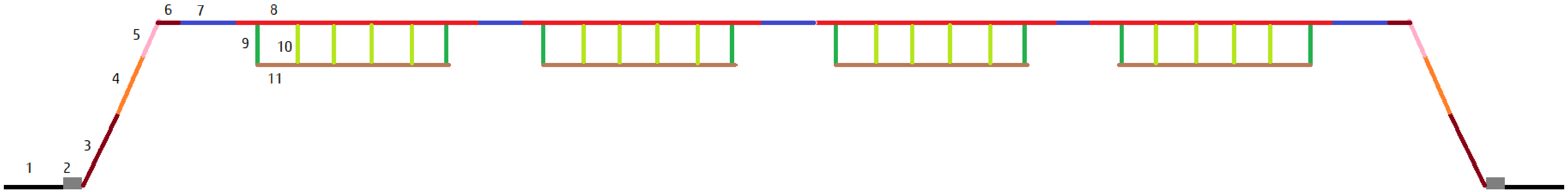

Table 12: lumped mass model elements

#	Length [m]	Type	E-mod[14] [Mpa]	Diameter [mm]	Fouling thickness[15] [mm]	Weight [kg/m]	MBL / SWL [kN]	Relative density [-]	Cf [static / dynamic]	Cd [perp / parallel]	Ca [perp / parallel]	Source
1	53	Stud link chain	2x64 000	58	0[1]	77	2953 / 879[2]	7.8	0.98 / 0.75	2.6 / 1.4	1 / 0.5	Sotra Studlink R3
2	2	Clump weight + chain	2x64 000	58	50[3]	792	2953 / 879[2]	2.57[5]	1 / 0.75	0.6 / 0.6[4]	0.5 / 0.5[4]	D = 1m H = 0.76 m Rho = 2400 kg/m3
3	19	Stud link chain	2x64 000	48	50	52.8	2063 / 842	7.8	0.98 / 0.75	2.6 / 1.4	1 / 0.5	Sotra Studlink R3
4	23	Dyneema – Low fouling	50 000	56	50	1.74	2490 / 866	0.98	-	1.8 / 0	1 / 0.5	Lankhorst Lanko-Force
5	7	Dyneema – High fouling	50 000	56	150	1.74	2490 / 866	0.98	-	1.8 / 0	1 / 0.5	Lankhorst Lanko-Force
6A		Buoy – Structural Component (rope)[8]	50 000	56	0	1.74	2490 / 866	0.98	-	0[7]	1 / 0.5	Lankhorst Lanko-Force
6B		Buoy – Buoyancy[9]	-	1000	150	235	-	0.3	-	0.6 / 0.32[10]	0.6 / 0.6	Floatex MMB12090609
6	3	Buoy	-	-	-	236.37	-	-	-	-	-	-
7	13 / 6 / 6 / 6 /13	Mooring Rope	1400	112	20[16]	5.96	1870 / 650	0.93	-	1.8 / 0	1 / 0.5	Lankhorst Tipto 8
8A		Horizontal Floater – Structural Component (rope)	1400	112	20[16]	5.96	1870 / 650	0.93	-	1.8 / 0	1 / 0.5	Lankhorst Tipto 8
8B		Horizontal Floater – Buoyancy	-	250	0[17]	8.3	-	0.17	-	1.17 / 0	1 / 0.5	PE 250x11.9
8	4 x 2 / 10 / 10 / 10 / 10 /10 / 2	Horizontal Floater	-	-	-	14.26	-	-	-	-	-	-
9	3.5[11]	Net - Outside	1600	49[12]	0	43	378 / 263	1.025	-	Confidential[13]	1 / 0.5	E-mod: Polyprop MBL: Lankhorst Tipto 8 / 12
10	3.5[11]	Net – Inside	1600	64[12]	0	86	651 / 453	1.025	-	Confidential[13]	1 / 0.5	
11	4x 10 / 10 / 10 / 10 / 10	Hercules rope	50 000	24	0[18]	0.98	174 / 121	1.85	-	1.8 / 0	1 / 0.5	Herculus rope

1) No fouling on ground chain. Any fouling is removed due to movement of chain
2) Includes a corrosion allowance of 10 mm (25 year / 0.4 mm) – Which reduces MBL to 2953 * 48^2/58^2 = 2022 kN
3) Fouling not on the bottom of the clump weight. Clump is modelled as a 1m diameter 0.76m height circular block
4) Clump weight assumed non-directional with relation to drag and inertial forces
5) Average density of steel chain and concrete clump
6) Includes a corrosion allowance of 1.5 mm (5 year / 0.3 mm) – Which reduces MBL to 1748 * 46.5^2/48^2 = 1630 kN
7) Cd and Ca assumed zero as this part is covered by the floater
8) Structural component assumed similar properties as Dyneema
9) The floater is actually 1.2 x 2.5m with 0.25m on either side of connections, but scaled to 1 x 3m to obtain a similar volume and frontal area. Total weight 555 kg + 150 kg for modifications.
10) Cd Parallel is scaled with surface area. Where Cd = 0.85 with frontal area.
11) Net length is 3m with 0.5m spacing between net and headrope+floater. 3.5m segment represents 3m net height. (net weight 10 kg/m2)
12) Vertical lines over 5m/10m are added and cross-sectional area is combined. Note: diameter is not used to calculate drag area. Drag area is calculated by assuming 10 kg/m2 and using weight [kg/m]
13) Drag coefficient for seaweed are based on Aqitec internal studies and are not shown for confidentiality
14) E-modulus is estimated based on the used condition in the case of synthetic rope.
15) Fouling density is 1300 kg/m3
16) Fouling thickness reduced to 20 mm for the head rope, as this line is cleaned during harvesting/seeding/maintenance. No fouling thickness over a single season is available in literature; during previous projects on the North Sea we experienced a maximum of 20 mm on synthetic ropes.
17) Prior experience shows the pipe is self-cleaning and no fouling is expected. This experience is based on the Smart Farm system implemented by Murre Technologies BV.
18) Bottom line of net. Seaweed on the net will prevent other fouling.

5 Global analyses

5.1 Introduction

Each load case is evaluated after the system is settled in the current, this takes a relative large amount of time, because of the dimensions and slack in the system. The tension in the system is stabilized for all direction after about 360s.

After the model stabilizes with only current, the wave height is ramped during 25s (~2 wave periods) up to the full wave height. Finally the full wave height is applied for 35s (~3 wave periods).

Pre-ramp	360s	(Current only)
Ramp time	25s	(Current + wave linearly ramps to full wave height)
Full	35s	(Current + full wave height)
Total	420s	

The pre-ramp time takes up a lot of computing time. For some load cases the current velocity is nearly the same. For this reason the current velocity during the pre-ramp time of some load cases is slightly different to allow using the same pre-ramp simulation for multiple load cases. Load cases for which this applies are indicated in the chapter ‘load cases’.

The loads through all elements are averaged over 0.1s to help visualize the results. With this averaging the model could overlook peak forces in some situations, however due to the flexibility of the system and based on the shape (steepness) of force-time curves this does not seem to be the case and this approach is correct.

5.2 ULS

Note that load case #27 has items #7 and #8 slightly above SWL (Safe Working Load). As good engineering practice a substantial amount of conservatism is included in the model. This conservatism is not required by the Regulatory Framework [6] and therefore load case #27 is re-evaluated with reduced conservatism as further increasing the rope diameter will result in an unpractical design.

We believe this approach is allowed as this leaves enough conservatism in the model, for example conservatism is applied through:

- Wave height at maximum water level is used (wave height at mean water level is allowed)
- Fully pre-tensioning the system by current and applying the maximum wave height multiple times in a row on the system. In reality the system will likely have some slack due to waves back-forth motion and waves with maximum height will not succeed each other.
- Estimate for fouling is based on stationary systems.
- High estimate for seaweed drag coefficient
- Permanent loads (gravity, buoyancy) are not evaluated with a reduced load factor in the ULS. Local analysis uses 1.15 on the global analysis results, where 1.00 is allowed for permanent loads.

The regulatory framework also provides multiple conservative approaches, for example:

- Material and load factors
- High estimate for wear on chain
- Combination of 10y/50y waves and 10y/50y current. The combination of high waves and high surface currents is very rare to find, as during high sea states the current typically is more constant with depth. Also many combination of directions of wave and current (co-occurrence) are very unlikely
- Overall selection of drag and inertial coefficients according DNV

Load case #36 is a re-evaluation of load case #27 with a reduction of the parallel drag coefficient of seaweed to reflect a nominal estimate. All other variables are kept the same in this load case.

Table 13: All load case results – Maximum forces during simulation are shown and indicated in kN

	1	2	3	4	5	6	7	8	9	10	11	12
Type	Studlink	Studlink+Clump	Studlink	Dyneema	Dyneema	Floater	Tipto	Tipto	Net	Net	Herculus	Center
Diameter	58 mm	58 mm	44 mm	50 mm	50 mm	50 mm	112 mm	112 mm	49 mm	64 mm	18 mm	112 mm
SWL[1]	879	879	842	866	866	866	650	650	263	453	121	650
Loadcase	Maximum force [kN]	Maximum force [kN]	Maximum force [kN]	Maximum force [kN]	Maximum force [kN]	Maximum force [kN]	Maximum force [kN]	Maximum force [kN]	Maximum force [kN]	Maximum force [kN]	Maximum force [kN]	Maximum force [kN]
1	181	182	183	182	182	180	175	173	37	23	16	143
2	703	695	682	643	661	597	531	526	40	42	27	221
3	330	329	325	304	313	282	251	253	78	50	30	177
4	350	344	342	338	333	328	317	315	24	26	19	216
5	456	449	448	437	436	433	423	423	45	50	32	347
6	307	290	288	271	269	266	260	263	69	45	27	128
7	325	326	326	325	325	324	318	318	39	35	23	263
8	515	514	514	507	511	502	491	489	66	70	53	367
9	208	210	210	209	208	215	227	227	45	34	27	132
10	502	510	511	494	512	447	413	410	62	55	36	288
11	575	575	574	565	561	549	524	525	48	58	39	481
12	392	394	402	405	405	406	407	407	22	13	10	367
13	320	320	322	322	323	325	327	327	72	43	32	289
14	465	466	467	467	467	465	462	462	21	16	12	301
15	332	327	326	316	315	311	302	301	50	31	27	250
16	185	186	188	188	188	187	182	182	19	15	8	123
17	725	721	716	677	697	640	570	564	48	56	33	256
18	635	629	625	589	606	548	491	489	34	41	25	217
19	349	350	351	351	351	351	348	348	48	40	28	290
20	301	302	302	298	299	294	282	281	36	26	18	218

21	650	638	631	604	618	559	504	503	35	41	27	236
22	284	285	286	286	286	285	281	280	33	27	14	216
23	428	429	430	429	430	428	426	426	49	36	25	207
24	681	670	663	625	642	586	513	514	39	44	29	218
25	706	699	690	644	667	610	552	551	42	44	27	234
26	369	368	363	348	357	339	324	323	33	36	16	205
27	658	658	663	667	670	670	670	671	34	33	22	534
28	502	496	491	449	459	418	361	363	38	35	24	184
29	448	446	443	423	423	421	418	418	34	39	28	305
30	389	383	377	356	366	335	303	295	49	35	23	141
31	177	175	171	156	164	144	127	128	28	28	12	108
32	571	564	564	564	564	563	564	565	31	24	20	490
33	184	178	179	181	181	183	185	210	35	26	20	210
34	266	249	245	241	241	235	221	220	37	29	21	137
35	370	355	352	339	333	318	296	295	58	41	28	131
36	630	630	634	638	640	640	641	642	28	29	19	508

1) *The safe working load of the system includes the material factor, load factor and corrosion allowance. For example item 01 has an MBL of 2953 kN and after including all factors this results in an SWL of 879 kN.*

During selection of the load cases the claim was made that the combination 50y wave/10y current is leading above 10y wave / 50y current. The table below shows the three load case sets. Only in the center of load case 21 a higher force is seen compared to the reference load case, however this is not one of the critical components during this load case. All other components show higher loads during the 50y wave / 10y current combination and for this reason we can conclude that the claim '50y wave/10y current is leading over 10y wave/50y current' holds for this location on the North Sea.

Table 14: effect of 50y wave / 10y current compared to 10y wave / 50y current – Maximum forces in each component during simulation are shown and indicated in kN

	1	2	3	4	5	6	7	8	9	10	11	12
Load case 2 50y waves / 10y current	703	695	682	643	661	597	531	526	40	42	27	221
Load case 21 10y waves / 50y current	650	638	631	604	618	559	504	503	35	41	27	236
Load case 7 50y waves / 10y current	325	326	326	325	325	324	318	318	39	35	23	263
Load case 22 10y waves / 50y current	284	285	286	286	286	285	281	280	33	27	14	216
Load case 8 50y waves / 10y current	515	514	514	507	511	502	491	489	66	70	53	367
Load case 23 10y waves / 50y current	428	429	430	429	430	428	426	426	49	36	25	207

For the simulations the nominal peak period is used according the MetOcean report. A sensitivity analysis is performed to check what the influence of a higher/lower wave period is. The table below shows the results and it is clear that a shorter wave period increases the forces, which is expected as local wave velocity in the linear wave theory increases with smaller wave periods. The forces in the main mooring components (1-8) increase up to 10% with reduced wave period. The effect is larger in the nets, as the nets have higher drag and are more susceptible to higher local velocity, an increase of up to 30% can be seen. However the nets are not one of the critical components and enough safety is left to absorb possible higher loads. The effect on the main mooring components on this (unlikely) event is within its safety factor boundaries.

Table 15: Effect of wave period - Maximum forces in each component during simulation are shown and indicated in kN

	1	2	3	4	5	6	7	8	9	10	11	12
Load case 17 Waveperiod = 11 s	725	721	716	677	697	640	570	564	48	56	33	256
Load case 2 Waveperiod = 12.5 s	703	695	682	643	661	597	531	526	40	42	27	221
Load case 18 Waveperiod = 14 s	635	629	625	589	606	548	491	489	34	41	25	217
Load case 19 Waveperiod = 9.25 s	349	350	351	351	351	351	348	348	48	40	28	290
Load case 7 Waveperiod = 10.74 s	325	326	326	325	325	324	318	318	39	35	23	263
Load case 20 Waveperiod = 12.25 s	301	302	302	298	299	294	282	281	36	26	18	218

A sensitivity of the water depth is performed next. The minimum and maximum water depth are compared to load case #2 with nominal water depth. A smaller water depth gives between 0% and 6% larger forces on the components. However these load cases are evaluated with the same wave height, a reduction in wave height is needed at lower water depth, which will bring the results closer together. These results are well within the safety boundaries on the components.

Table 16: Effect of water depth - Maximum forces in each component during simulation are shown and indicated in kN

	1	2	3	4	5	6	7	8	9	10	11	12
Load case 25 Water depth = 32.8 m	706	699	690	644	667	610	552	551	42	44	27	234
Load case 2 Water depth = 35.0 m	703	695	682	643	661	597	531	526	40	42	27	221
Load case 24 Water depth = 38.1 m	681	670	663	625	642	586	513	514	39	44	29	218

When reviewing all load cases we can conclude that the system satisfies the criteria as set in the Regulatory Framework [6] and Design basis [7].

5.3 ALS

The ALS load cases were expected to be similar to ULS load cases with in-line currents, however environmental loads are lower and a portion of the system is not connected anymore. Simulation results show a similar trend, with loads lower compared to load case #11 . Component #7 and #8 show the relative highest load compared to the SWL at 53%. ALS is not a critical load case for dimensioning the components.

Table 17: ALS load case results – Maximum forces during simulation are shown and indicated in kN

	1	2	3	4	5	6	7	8	9	10	11	12
Type	Studlink	Studlink+Clump	Studlink	Dyneema	Dyneema	Floater	Tipto	Tipto	Net	Net	Herculus	Center
Diameter	58 mm	58 mm	44 mm	50 mm	50 mm	50 mm	112 mm	112 mm	49 mm	64 mm	18 mm	112 mm
SWL[1]	879	879	842	866	866	866	650	650	263	453	121	650
Loadcase	Maximum force [kN]	Maximum force [kN]	Maximum force [kN]	Maximum force [kN]	Maximum force [kN]	Maximum force [kN]	Maximum force [kN]	Maximum force [kN]	Maximum force [kN]	Maximum force [kN]	Maximum force [kN]	Maximum force [kN]
201	290	286	286	287	287	287	285	285	33	30	21	235
202	337	337	339	339	341	343	344	344	27	26	17	181
203	143	142	141	137	131	123	119	118	8	8	4	58
204	213	212	212	212	211	209	201	200	32	22	15	188
205	278	279	280	280	280	282	283	283	38	29	22	182
206	151	152	153	153	153	148	136	135	39	20	13	3
207	218	219	220	221	222	228	229	229	26	25	17	2

208	93	93	93	91	87	76	72	71	8	7	4	1
209	339	335	333	329	311	282	231	230	32	27	14	3
210	220	222	224	224	224	220	209	209	38	24	18	4

5.4 FLS

Load cases 101 – 106 are evaluated per item. For each item the minimum and maximum force are extracted from the simulation results for the last 30 seconds of the simulation. The difference between the minimum and maximum force is used as the stress range and indicated in the table.

Table 18: Evaluation load cases

Waveheight [m]	m	1.8	1.8	4.0	4.0	6.6	6.6
Load case [-]	-	105	103	101	102	106	104
Wave-direction	-	In-line	Perpendicular	In-line	Perpendicular	In-line	Perpendicular
ΔF Studlink Chain 58 mm[1]	kN	18	24	48	24	67	33
ΔF Studlink chain 48 mm	kN	21	11	49	12	61	15
ΔF Dyneema rope 56 mm	kN	18	9	48	10	64	14
ΔF Mooring rope 112 mm		31	7	45	12	76	17
1) Note that the method for handling friction with the seabed can cause the model to overestimate the forces through the ground chain.							

The results are linearly interpolated with wave height for the bins that are not simulated. The first bins are interpolated between waveheight of 0m (= 0 kN) and the first simulation.

Table 19: Force per bin

Bin No.	Hs	ΔF Studlink Chain 58 mm	ΔF Studlink chain 48 mm	ΔF Dyneema rope 56 mm	ΔF Mooring rope 112 mm
[-]	[m]	[kN]	[kN]	[kN]	[kN]
1	0.6	8	7	6	10
2	0.8	11	9	8	14
3	0.9	12	11	9	16
4	1	13	12	10	17
5	1.2	16	14	12	21
6	1.4	19	16	14	24
7	1.6	21	19	16	28
8	**1.8**	**24**	**21**	**18**	**31**
9	2.1	27	25	22	33
10	2.3	29	27	25	34
11	2.6	33	31	29	36
12	2.9	36	35	33	38
13	3.2	39	39	37	40
14	3.4	41	41	40	41
15	3.7	45	45	44	43
16	**4**	**48**	**49**	**48**	**45**
17	4.3	50	50	50	49
18	4.5	52	51	51	51
19	4.7	53	52	52	53
20	4.9	55	53	54	56
21	5.2	57	55	55	59
22	5.3	58	55	56	61
23	5.9	62	58	60	68
24	**6.6**	**67**	**61**	**64**	**76**

Results for the fatigue life are indicated in the table below.

Table 20: Life

Component	Stud link chain Bottom chain 01-002-002	Stud link chain Catenary chain 01-002-006	Dyneema rope Anchor line 01-002-008	Mooring rope Head rope 01-004-001
Diameter	58mm	48mm	56mm	112mm
Material/ grade	R3	R3	LankoForce (Dyneema yarn)	TiptoEight (Polyolefin)
MBL	2953kN	2063kN	2490kN	1870kN
Life @ DFF=3 Load spectrum	37.8 y*	27.7 y**	1.16 * 10^17 y	2.46 * 10^15 y
*included is reduction for 25 year wear and corrosion **included is reduction for 10 year wear and corrosion				

From the analysis it can be concluded that the working life limits exceeds the commercial life of the farm. This is mainly due to the fact that the nominal conditions are fairly low compared to the ULS conditions + safety margins. For life time of the chain and rope it is expected that wear and corrosion are leading for the end-of-life of the mooring components.

6 Analysis SLS

Serviceability limit states include loads transferred by a vessel to the mooring construction.

Table 21: loads during service

		Medium workboat KRVE86	Large workboat Damen Multicat	RWS Rotterdam - IMO 8609888
Displacement	[tonnes]	85	200	514
Bollard pull DP	[tonnes]	12	35	8 (est. thrusters)
Tugger winch capacity	[tonnes]	10	15	-
Crane capacity	[tonnes]	9.4	10.3 @ side ship	10
Projected under water area	[m2]	34	53	120
Drag 1,3m/s current	[tonnes]	3	4.6	10.4

In the table above a list with three typical vessels for operations is included. The ship has the capacity to exert loads to the system in four ways, these are listed in the table below.

Table 22: loads transferred from ship to seaweed system.

	Event	Max. capacity listed ships	Target for operational load limit
		[tonnes]	[tonnes]
1	Being moored to the long line and use thrusters	35	Limit line pull to 15 tonnes
2	On DP and use of the tugger winch to pull the seaweed system close by	15	Limit line pull to 15 tonnes
3	On DP and use the crane to lift parts of the seaweed system in the air	10.3	Limit hoisting force to 10 tonnes
4	Being attached to the longline, making use of the seaweed system anchors and being dragged by the current.	10.4	Limit line pull to 15 tonnes

The ship does not transfer loads directly to the net. Loads are always transferred to the main components of the system, namely the head rope. The forces are transferred through the head rope, buoy and anchor chains to the anchor. The component with the lowest MBL that transfers the SLS loads is the head rope (1870 kN). The MBL is well above the loads indicated in the table above (35 tonnes ≈ 350 kN), however it is still advised to limit the load during service according the right most column of the table.

The loads during harvesting of the seaweed were evaluated during a test in 2022. It was found that the ship and harvesting machine combination introduced a peak load of 32kN (3.2 tonnes).

7 Analysis buoyancy

Buoyancy elements are the 2x catenary buoys and 4x pipes. The analysis includes the maximum marine growth from [7].

Table 23: buoyancy [kg]

		Loss of pipes				
		0	1	2	3	4
Loss of buoy floatation	0	-9224	-6958	-4693	-2427	-162
	1	-7356	-5091	-2825	-560	1706
	2	-5489	-3223	-958	1308	3573

In nominal conditions the system has 9224kg buoyancy. The system has sufficient buoyancy to maintain floating after loss of 50% buoys and 50% pipes. This is in line with the regulatory framework.

8 Local analyses

8.1 Matrix highest loads from ULS

Table 24: highest loads from ULS

Component	MBL	Corrosion allowance^{1}	Load factor^{1}	Material factor^{1}	SWL	Maximum result (from global analysis)
	[kN]	[mm]	[-]	[-]	[kN]	[kN]
Pile						725
Studlink Chain 58 mm	2953	10	1.15	2	879	725
Studlink chain 48 mm	2063	1.5	1.15	2	842	716
Dyneema 56 mm	2490	-	1.15	2.5	866	697
Buoy (internal)	>1541	10	1.15	2	>670	670
Mooring rope 112 mm	1870	-	1.15	2.5	650	642
Net		-	1.15	1.25		
Clump (connection)	68	10^{2}	1.15	2	-	

1) Source: [6] and [7]
2) For steel structural component

8.2 Clump weight

The clump weight is attached to the main chain. This attachment transfers all the forces acting on the clump weight to the chain.

When on the seabed the maximum friction is 1.00*1340*9.81 = 13145 N

When near the surface during a storm, maximum drag force is

Fd = 0.5*0.6*1025*1.77*5^2 = 13606 N

Cd = 0.6

Rho = 1025 kg/m3

A = 1.5^2*pi/4 = 1.77 m2 (D=1.5 m)

V = 5.0 m/s (Maximum local wave velocity according linear wave theory)

The connection to the clump weight should be selected with a SWL of 13.6 kN. According the Regulatory Framework a safety factor of 2.0 is needed on steel connections plus corrosion allowance. To be on the safe side a safety factor of 5.0 is selected.

MBL = 68 kN

8.3 Buoy

For the buoy a few initial calculations are performed to check feasibility, however final design of the buoy is performed by the supplier and should be conform the specifications in the table below. The final design should include weld calculations and details. Refer to [6] and [7] for properties that are not shown in the table.

Table 25: Minimum specifications of buoy

Specification		
Corrosion allowance on diameter	mm	10
Corrosion allowance on radius	mm	5
SWL	kN	670
MBL	kN	1541
Design life	years	25
Hydrostatic pressure depth	m	35

The selected deep water floats are of the type Floatex MMB12 (MMB12090609). The standard internal steel part is not according the specifications and needs to be custom designed.

8.3.1 Pipe body

Body material is S355

279 x 20 mm => 269 x 15 mm including corrosion allowance

$A_{tensile}$ = (269^2-239^2)*pi/4 = 11969 mm^2

σ_{mises} = F/A = 1541*10^3 / 11969 = 129 Mpa

The minimum yield stress of the material (S355) with thickness 20mm is 345 Mpa. The expected stress in the item is below the yield stress, thus is acceptable.

8.3.2 Eye calculation

Eye material is S355

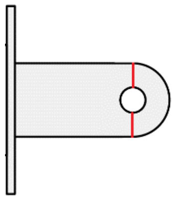

Figure 4: Tension area of eye, indicated in red

$A_{tensile}$ = 2*2*(40-10)*(57.5-10) = 5700 mm^2 (includes corrosion allowance)

σ_{mises} = F/A = 1541 / 5700 = 270 Mpa

8.3.3 Pin calculation

Pin material is StE690

A_{shear} = 2*(65-10)^2*pi/4 = 4752 mm^2 (includes corrosion allowance)

σ_{mises} = sqrt(3)*F/A = 562 Mpa

Figure 5: Design of buoy

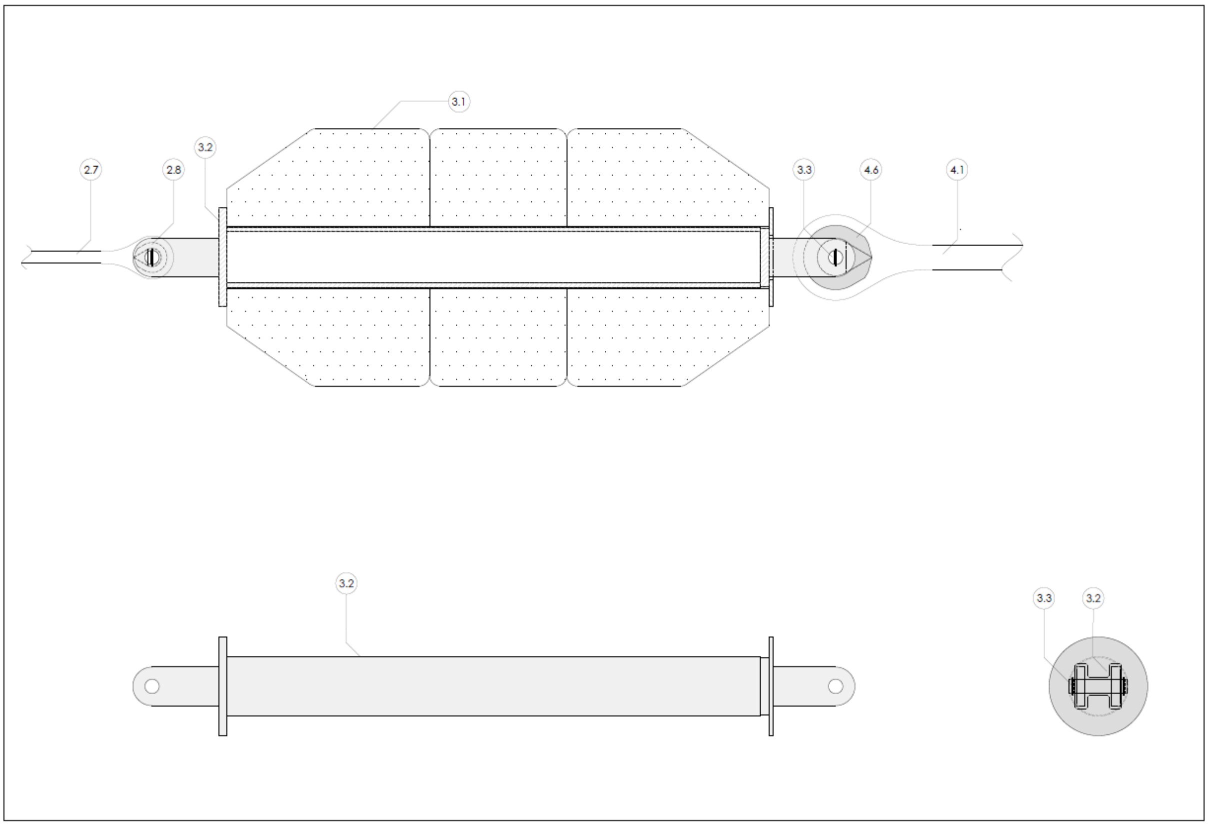

Table 26: parts buoy

3	01-003	Buoy assembly	2		Material *	
3.1	01-003-001	Floaters		1 set	PE / PUR foam	
3.2	01-003-002	Weldment		1	Steel S355	X
3.3	01-003-003	Pin		2	Steel StE690	X
* For all materials: equivalent alternatives can be used						

It is advised to include a part to fill-out the clearance between pin and thimble.

8.4 Rotation part

A rotating part is required to allow the pipe to rotate and transfer axial loads on the pipe to the head rope. Loads in perpendicular direction to the pipe centerline are transferred via the loops connecting the head rope. The flexible nature of the pipe and head rope limit bending forces to a minimum.

The pipe is not an isolated element in the global analyses, therefore it is not possible to extract loads acting on the pipe solely. The axial loads are estimated based on the displacement of the pipe:

- (The maximum particle velocity for a 50y wave is estimated using Airy wave theory at 5,0m/s. Drag forces on a slender cylinder is a 0.85. Using the drag formula this results in a load of 530N.)
- The displacement of the pipe is 2.45m3. It can be argued that when half the pipe is dragged unevenly under water this is a load that may act in axial direction. 0.5x2.45x1025x9.81=12.3kN. Including a quasi-static load factor [6] of 1.43 this results in axial load case of 17.6kN.

The original design of the rotation part of the pipe system was very basic. The pipe itself was used as bearing surface and lightweight clamping flanges and coupling to the head rope were included. The original design included 100m pipes. Since the dynamics in offshore conditions are known to result in more wear and loading on the rotation part a redesign is proposed. Engineering practice for bearing design in seawater is to use a soft plastic material with grooves and a hard metal or ceramic counter surface. Abrasive elements like sand grains are impressed in the soft plastic and rolled out of the bearing grooves. Common materials for the plastic bearing are UHMWPE and brand names Hakorit, Thordon and D-glide. For the metal bearing part a stainless steel like AISI316 can be selected.

Figure 6: Design of swivel on pipe

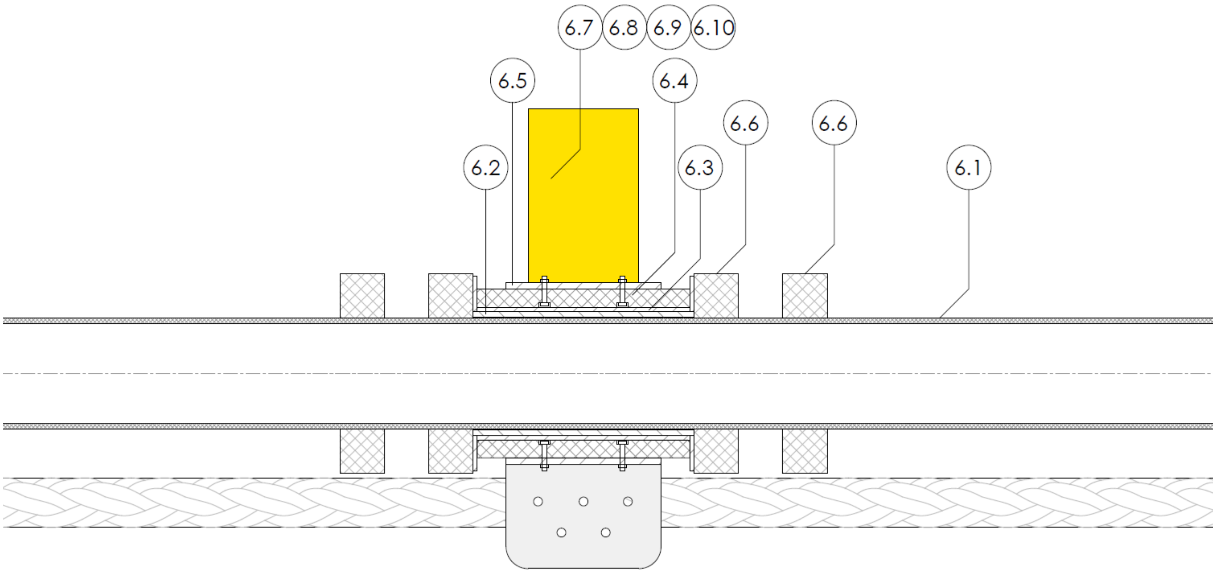

Table 27: Considerations design

6	01-006	Pipe assembly	#	Material*	Considerations
6.1	01-006-001	Pipe Ø250	1	HDPE	
6.2	01-006-002	Pipe Ø280	1	HDPE	To be glued to part 6.1
6.3	01-006-003	Wear sleeve	1	AISI316	Weldment. 10mm thickness pipe and plates are selected. This part is considered stronger than the Ø250 pipe.
6.4	01-006-004	Rotating element	1	UHMWPE	Axial surface is 15.315mm2. Axial contact stress is 1,15N/mm2. Far below the typical yield stress of UHMWPE ~20N/mm2
6.5	01-006-005	Brackets	2	AISI316	The bracket is connected by means of a rope spliced through the head rope. Spliced rope should have a MBL of 44kN. (17.6kN multiplied with material factor 2.5)
6.6	01-006-006	Clamping flange pipe	4	HDPE	Able to transfer 17.6kN. Relaxation of the clamp and pipe make a transfer of load by means of friction impossible. A arrangement should be included to increase the friction between flange and pipe. Option are to use metal pin inserts that embed in pip or an inlay of high friction material.
6.7	01-006-007	GNSS unit	1		Connected to clamping flange
6.8	01-006-008	Camera unit	1		Connected to clamping flange
6.9	01-006-009	Radar reflector	1		Connected to clamping flange
6.10	01-006-010	Top light	1		Connected to clamping flange
* For all materials: equivalent alternatives can be used					

8.5 Net

In load case #11 we find a maximum of 260 kN transferred by a single 50m net to the head rope. In this load case the edge of the net transfers 50 kN at its peak. These numbers align with hand calculations, which predict a peak of about 250 kN per net. Load factor (1.15) and material factor (1.25) need to be included.

The net should fulfill the following requirements:

- MBL of 7.5 kN/m of net
- MBL of outer ropes 72 kN

C-links from the company Asano have been conceptualized in order to make the net detachable. The links have a limited capacity and use of shackles or other connections should be considered. Other solutions can be evaluated, such as aquaculture shackles, omitting the detachability or custom design snap-fits. In discussion with the net supplier the detail design should be made.

8.6 Pile

The pile anchor is described in a separate document as the pile is very dependent on soil type.

8.6.1 Criteria pile

- Highest ULS load on the anchor pile is 725kN. This load is set to be the maximum expected lateral load.
- The safe working load of the bottom chain after 25 year is 1011kN.
- Load factor according to [6] is 1,15
- In order to prevent pile pull-out, a safety factor of at least 1.5 is required between the expected load and the pile pull-out load [4]. Note that this factor supersedes the 1.15 factor mentioned in the preceding point
- The integrity of the pile will be checked against ISO 19902 [5].
- There is no limit for the allowable pile deflection. [4] notes that requirements for foundation piles are set by serviceability requirements of the connected structures. For this project, a tilt or permanent deflection of the pile is not considered to be an issue in terms of performing the intended function.
- Including multiplication of safety factor the lateral pull-out capacity of the pile should be minimal 725x1,5= 1088kN

9 Conclusions

The Seaweed Production System is evaluated according the regulatory framework and design basis. The design meets most criteria, however further investigation is needed for some components to confirm compliance.

- Pile design
    - Location specific soil data needs to be used to calculate holding capacity. Structural design of the pile should be checked for ULS, ALS and FLS. The connection with the catenary chain should be designed.
- Buoy design
    - Basic calculations are performed on the buoy design, however the buoy should be selected and designed together with a supplier according the given specifications in this document.
- Net design
    - The net should be designed together with supplier, general specifications are given in this document. The integration in the operation (seeding, harvesting) and manufacturability should be evaluated.
- Clump weight connection
    - A connection to the chain needs to be selected that meets the specifications set in this document.
- Rotation part and HDPE pipe
    - The rotation part and integration with HDPE pipe is conceptualized. The custom parts should be further detailed and evaluated by the supplier.
- Connections in the catenary
    - The catenary assembly is constructed without connection elements (such as kenter, pear shackles) and other (weakening) elements. Based on the requirements the supplier should make a dedicated design with matching long-term-mooring (LTM) elements.
- Operational and maintenance
    - O&M has been considered in the design , however a thorough review by offshore specialists is recommended.
- MARIN check
    - At the time of writing MARIN is performing a check on the dynamic simulations. The outcome of their work should be used to verify this report.

Summary of findings

- ULS
    - The design is evaluated for 144 wave and current load combinations. The used model includes conservative approach for tension build-up, fouling, seaweed drag and inclusion of permanent loads. Sensitivity analyses has been done for water depth and wave period. The design is in compliance with the regulatory framework [6] and design basis [7].
- ALS
    - Loads in case off failure close to the buoy and in the centre and of the system are evaluated. The loads are lower than in case of ULS. ALS is not a critical load case for dimensioning of components.
- FLS
    - Wear and corrosion are expected to determine the actual end-of-life of the mooring components. The design is in compliance with the regulatory framework [6] and design basis [7].
- SLS
    - Loads during servicing have been evaluated. Limitations for line pull and hoisting force have been stated. In case larger ships, cranes and winches will be used it is recommended to include hoisting provisions on the seaweed system. The design is in compliance with the regulatory framework [6] and design basis [7].
- Buoyancy
    - The design is evaluated for reduced buoyancy. The system remains floating without the catenary buoys and 2 (of 4) pipes. The buoyancy of design is in compliance with the regulatory framework [6] and design basis [7].

5. Note on pile pull-out load

The removal of foundation piles of offshore structures is usually only partial. Piles are cut at a depth of a few meters below the natural seabed, and only the upper section is removed. This mitigates both the required lifting force and the environmental impact of structures remaining above the mudline. This project considers the complete removal of a pile embedded deeper into the seabed. At such depths the soil-pile friction force is significant and will drive the selection of high capacity lift equipment.

It is also noted that there is significant uncertainty in the prediction of the soil resistance when pulling the pile. Codes and standards used in the design of offshore foundations use the lower bound of soil resistance, resulting in safe designs. It is, however, likely that the actual soil resistance is a multiple of that predicted by the design standards. The following figure, taken from [O1], shows the calculated coefficient of lateral earth pressure (K) for several laboratory experiments of pile extraction. Where K is usually taken to be 0.8 in design calculations, approximately half of the data points are located between 1.5 and 2.5, or 2 to 3 times what is considered in design calculations. An outlier of 5 times the design phase calculations is also presented for a densified sand.

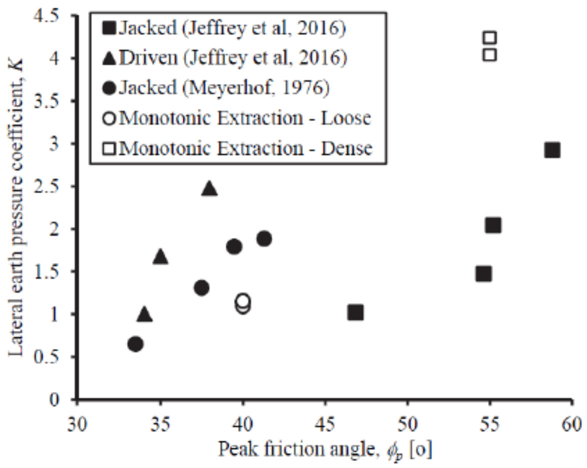

Figure 6 Lateral earth pressure coefficient determined for pile extraction tests

Another effect that may increase axial capacity is known as 'ageing', where gradual restructuring of the soil around the pile increases capacity over time. Ageing may be a part of the elevated extraction force required, as noted before and presented in Figure 6, or may be a separate factor to be considered in addition. This phenomenon is still quite poorly understood, and the available test data is for pile not experiencing any loading [O2], whereas the anchor pile will be subjected to lateral loads from the seaweed cultivators. This may break the soil restructuring that has occurred up to that point, and as such negate the effects of ageing.

It is clear that there is a large uncertainty in removing the complete pile via a vertical pull out. It is recommended to used a factor 4 between the predicted pull-out force and the Working Load Limit of the components used in the pull-out. This is expected to be a sufficient margin on the required pull-out force.

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