Techno-Economic mooring configuration and design for floating offshore wind turbines in shallow waters – Final Report

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NOWRDC Project:
Techno-Economic mooring configuration and design for floating offshore wind turbines in shallow waters

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Keywords

Shallow water mooring systems, chains, synthetic ropes, mooring anchors, offshore floating, wind turbine, Orcaflex software.

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Executive Summary

The US East Coast has several leased wind energy sites in water depths ranging from 60 - 100 m, where floating wind turbine systems are feasible. For these systems, designing suitable mooring systems for shallow water depths within the constraints of survival hurricane conditions can be challenging. This study compared pure chain and mixed chain-synthetic mooring systems to predict the maximum extreme position and effective tension for different cases. Synthetic ropes, which offer a low cost and superior performance alternative compared to chain and wire ropes, were utilized dominantly in our mooring design. In this study, we used an IEA 10 MW wind turbine on a semi-submersible floating offshore structure in two sites: Nantucket, MA (WD = 60 m), and Monhegan, ME (WD = 100 m). For the configurations we conducted detailed numerical simulations for three different load design cases DLC 1.6 50-yr return period, DLC 6.1 50-yr return period, and SLC I.1 500-yr return period. The wind used in simulations was a turbulent wind based on Kaimal spectrum with different mean wind speed and turbulent intensity based on each load case and return period. The JONSWAP spectrum was used to model waves with different significant height and peak period based on each load case. A uniform current was also considered for all simulation cases. For extreme value predictions, three 1-hour simulations with different seed numbers for the SLC I.1 500-yr return period were performed. The MPME (most probable maximum extreme) value is an extreme value statistic commonly used in the offshore industry. The top 10% of the peaks above a threshold value were further analyzed using a Weibull distribution to obtain MPME values. The effects of mooring material, number of lines per column and the water depth on the MPME as well as cost issues are discussed in the report.

1 Introduction

Offshore wind development is attractive due to higher speed and consistency of winds over sea than on land. This is clear from an expert survey conducted under IEA Task Force 26 and reported in (Wiser et al. 2016). Furthermore, larger turbines (10 – 15 MW) for offshore applications could become the norm in the future. For offshore wind, one technology that can support a range of drivers for LCOE reduction would be cost-efficient sub-structures. This could become more critical in the future, as a sub-structure should also support ease of installation and hookup of larger wind turbines that those used presently. Various analyses suggest (e.g., Damiani et al. 2016) that selecting a suitable sub-structure (and its components) is one of the most important aspects for successful U.S. offshore wind development. This aspect is inherently multidisciplinary, since it encompasses technical design aspects as well as economics, logistics and installation challenges.

Up to a depth of 50m, bottom founded sub-structures like monopiles, and jackets are considered technically and economically feasible. Monopiles increase in weight quite dramatically when water depth and/ or rotor diameter increases (e.g., Myhr et al. 2014) with an accompanying increase in costs (Damiani et al. 2016). While larger monopiles for supporting turbines greater than 6 MW in waters deeper than 30 m have been contemplated in Europe, cost increases and infrastructure challenges are expected (Seidel 2014). Since US does not have a manufacturing facility for monopiles, such monopiles need to be transported in segments and installed in US waters, which would cause challenges in schedules and cost.

Floating sub-structures offer tremendous promise when the LCOE of a farm of 100 or more turbines are considered (Myhr et al. 2014). Floating sub-structures are capable of being upscaled for larger turbines and give flexibility to a developer in locating their farm as the structures can be customized to any water depth. Since floating support structures are necessarily anchored to the seabed by means of anchoring and mooring systems, there is a need to evaluate suitable mooring systems for FOWTs. Designers of FOWT support sub-structures base their principles on practices used in the offshore oil and gas industry, where such systems are normally optimized for a range of applications. Regulatory guidelines developed for the FOWT industry are also based on precedents from the offshore industry. It is then prudent to utilize the knowledge and know-how of mooring system designs from the offshore oil and gas industry and evaluate applicability to the offshore wind industry.

Mooring system failures in the offshore environment occur more often than expected and cause higher inspection, maintenance, and replacement costs. Collaborators of a joint industry project (Ma et al. 2013) analyzed 21 mooring line incidents and failures that were recorded in the public domain and occurred between 2001- 2011. Causes of failures range from errors in installation, poor maintenance, manufacturing defects, and stresses caused by bending and fatigue. Failures were prevalent in all mooring types (chains, wires, and fiber ropes) and affected various components (chain links, fairleads, and shackles). The resultant annual probability of failure was found to be uncomfortably high at 0.3%. Based on the experience of developers, regulators, researchers, and engineering companies that support this project, these past incidences call for a judicious approach to developing reliable mooring systems for the FOWT industry.

Due to the different nature of FOWTs compared to oil and gas platforms, it is clear that the mooring technologies are not always directly transferable or sufficiently reliable, viable or affordable. These challenges provide the motivation to develop and test alternative forms of mooring compliance and novel anchoring systems that are not only cost effective but also allow for more economical methods in installation, maintenance, and decommissioning. Key challenges of shallow water mooring systems as well as notable differences between FOWT and oil and gas platforms, whose designs has been heavily utilized regardless, are noted as following:

- FOWTs operate in shallower water depth compared to established standards of oil and gas platforms.
- Fatigue load characteristics from transferred wind turbine loads or increased out-of-plane-bending via increased yaw motions can impact the performance and integrity of the mooring systems. Oil and gas platforms do not concern with these factors.
- The common approach via decoupled, quasi-static, or frequency domain analysis in offshore oil and gas production may introduce large errors when modeling the coupling effect and non-linear response of a FOWT.
- For the catenary mooring, the portion lying on the seabed has to be long enough to avoid being totally lifted up during its lifetime and to prevent the anchor from taking any vertical load even in the most extreme conditions.
- For taut mooring design, while the shorter mooring line and smaller footprint might be attractive, the rope stiffness is inversely proportional to the line length and could result in very stiff mooring lines and increasing line tensions under extreme loads.
- The mooring system should be stiff enough to limit the platform horizontal excursions due to the influences of the mean wind and wave loads, as well as the second order wave-induced motions. On the other hand, the design also has to be compliant enough to allow for wave frequency motions of platform and to avoid large mooring tensions resulting from first order wave loads. The criteria are more challenging in shallow water for both catenary and taut mooring systems. With the same horizontal offset at the fairlead, mooring line in shallow water will be subjected to higher line tension, which may lead to potential breaking.

- The leeward mooring line should not experience slack, which may lead to large snap tension.
- Limit the use of clump weights and buoys to avoid liability to others in the case of breakaway.
- Lack of a well-established guideline and numerical programs for the time-variant or viscoelastic effects of synthetic rope behaviors.

The NOWRDC funded project is a feasibility study of synthetic mooring system for a generic semi-submersible floating platform supporting a 10 MW wind turbine. Based on the metocean studies by Manwell et al. (2019) and Arwade et al. (2021), two offshore sites were selected for the study. Table 1 summarizes selected site information and data source of metocean analysis. A design basis for development of a suitable mooring system for a floating platform capable of supporting a 10MW wind turbine in US waters for a lifetime of 25 years was first established. As a next step, a generic semi-submersible was sized. Based on various technical and economic considerations including design criteria, applicable rules and regulations, design procedures, analysis methodologies, load cases, site information, water depth, environmental conditions and cost, two mooring systems for each floater type were proposed. This report summarizes the floater and mooring geometry, as well as simulations conducted to study the technical performance of various mooring systems. The report concludes with cost implications and recommendations.

Table 1. Selected site information

Site	Location	Water Depth (m)	Data source	Duration wave/wind (yrs.)
Monhegan	43.750 N 69.300W Gulf of Maine, ME	100	Purpose-deployed buoy	3/3
Nantucket	40.504 N 69.248W 54 NM SE of Nantucket, MA	74.7	NOAA data buoy 44008	35/32

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2 Turbine, platform and mooring system

2.1 Turbine and platform Information

The IEA 10 MW wind turbine (Bortolotti, et al. 2019) was chosen for this simulation. The turbine was designed for the IEA Wind Task 37 based on the DTU 10-MW. The IEA 10-MW is rated at 10MW electric power and designed for the IEC class 1A. It features a direct-drive generator and an improvement of the controller over the original DTU 10 MW. The specifications of the turbine are provided in Table 2.

The semi-submersible platform design (Figure 1) is scaled-up from the 5MW DeepCWind semi-submersible FOWT model, and the semi-submersible platform dimensions and mass properties were selected considering that the static heel for the rated wind thrust is less than 6 deg and the heave and pitch natural frequencies avoid the wave frequency ranges. The draft of the platform is 22.0m. The tower is installed at an elevation of 32m above the keel to the main column (green) of the platform. The platform consists of a main column and three side columns (blue), which are attached to the main column through a series of smaller diameter cross members. At the base of the three side columns, cylinder types of pontoons are attached, and the pontoons have 25m diameter, which is larger than the side column diameter, 14m. They help to suppress motions, especially, heave, roll, and pitch motions. Principal dimensions and mass properties of the platform are summarized in Table 3.

Table 2 Summary of Reference Wind Turbine Specifications

Turbine	**Unit**	**IEA**
Rating	**MW**	**10**
Rotor Orientation	-	Upwind
Configuration	-	3 blades
Rotor Diameter	m	198
Hub Height	m	119
Cut-in Wind Speed	m/sec	4
Rated Wind Speed	m/sec	11
Cut-out Wind Speed	m/sec	25
Rotor Speed Minimum	rpm	6.00
Rotor Speed Maximum	rpm	8.68
Hub Mass	tonne	81.7
Nacelle Mass	tonne	542.6
Blade Mass	tonne	47.7
Tower Mass	tonne	628.442
Tower Height	m	115.63

Tower Top Thickness	mm	40
Tower Top Diameter	m	5.5
Tower Bottom Thickness	mm	70
Tower Base Diameter	m	8.3
Tower CG (% from Base)	%	41.6

Table 3 Principal dimensions and mass properties of 10 MW DeepCwind semi-submersible floating wind turbine

Item	Unit	10MW DTU
Draft	m	22.0
Column Diameter	m	14
Pontoon Diameter	m	25
Tower Connection	m	9.0
Column Separation	m	60
Free Board	m	10.0
Platform steel Mass	T	4,680
Platform Displacement	m^3	21,110
Platform KG	m	7.3
Platform Roll Gyration	m	25.7
Platform Pitch Gyration	m	25.7
Platform Yaw Gyration	m	35.3
Metacentric Height (GM)	m	7.8

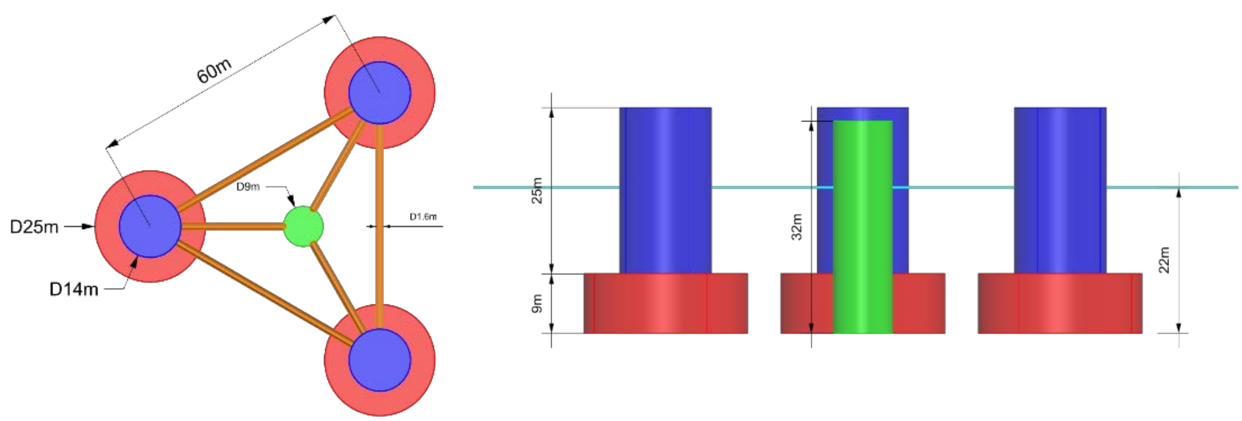

Figure 1 Plan (left) and side (right) view and dimensions of the semisubmersible platform

2.2 Mooring configuration

A conventional mooring system was developed as a base case. As is common practice in offshore oil and gas, our study considers redundancy in the mooring system, thus grouped into three clusters, consisting of three mooring lines each. The azimuth angle of the mooring line is separated by 5 degrees, and the heading difference is 120 degrees between mooring clusters. The mooring fairlead is assumed to be 9 meters above the keel. Simulations of this mooring system were conducted to validate and verify our system, and results may be found in Sharman et al. (2022).

The synthetic mooring system chosen for simulation is composed of platform chain – heavy chain – polyester rope – anchor chain. In this mooring system, the heavy chain makes the mooring system softer and can reduce the polyester rope size. A schematic of the mooring system is shown in Figure 2. The fairlead is placed at the top of the column to increase the line length and provide more opportunity to reduce line tension. The mooring system properties are summarized in Table 4. The study initially considers nine (9) lines distributed equally in three mooring cluster (groups), gradually reducing this to one line per cluster.

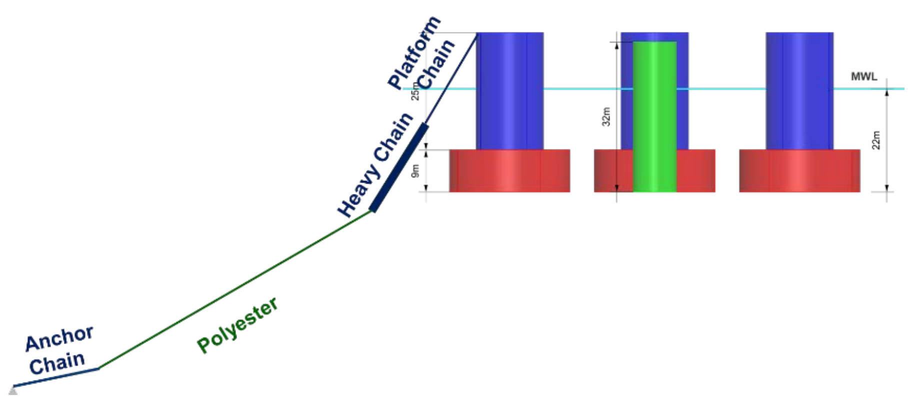

Figure 2 Platform chain – heavy chain - polyester rope – anchor chain mooring line Configuration

Table 4. Semi-submersible Synthetic Mooring system properties

Mooring System	Mooring Line Segment	Diam. (mm)	Static EA (kN)	Dynamic EA (kN)	MBL (kN)	Dry Weight (kg/m)	Wet Weight (kg/m)	Length (m)
Chain	Platform Chain	160	1.914E+06	NA	2.139E+04	648	564	34
Heavy Chain	Heavy Chain	210	3.740E+06	NA	2.911E+04	883	516	24
Polyester Rope	Polyester Rope	240	2.046E+05	5.338E+05	1.779E+04	41.31	11.19	776
Chain	Anchor Chain	160	1.914E+06	NA	2.139E+04	648	564	37

2.3 Environmental Conditions

Table 5 summarizes environmental conditions for mooring sizing. As discussed in Sharman and Koo (2021), two DLC and one SLC cases are considered.

Table 5. Environmental conditions for mooring sizing

Site	Load Cases	DLC/SLC	Ret. Period (yr)	Wind Speed (m/s)	Wind spectrum	Wind heading (deg)	Wave Height (m)	Peak Wave Period (sec)	Jonswap γ	Wave heading (deg)	Current Speed (m/s)	Current heading (deg)	Current profile
Monhegan	Operation	1.6	50	10.6	Kaimal	0, 180	8	12.7	2.2	0, 180	0.3	0, 180	constant
	Parked/Idle	6.1	50	40	Kaimal	0, 180	10.2	14.1	2.2	0, 180	0.45	0, 180	constant
	Survival	I.1	500	45	Kaimal	0, 180	12	15.3	2.2	0, 180	0.5	0, 180	constant
Nantucket	Operation	1.6	50	10.6	Kaimal	0, 180	7.6	10.3	2.2	0, 180	0.41	0, 180	constant
	Parked/Idle	6.1	50	40.8	Kaimal	0, 180	11.5	12.7	2.2	0, 180	0.45	0, 180	constant
	Survival	I.1	500	44.6	Kaimal	0, 180	12.7	13.3	2.2	0, 180	0.45	0, 180	constant

Note: heading angle would follow the convention of azimuth shown in the figure. So 180 deg would correspond to wave/current/wind traveling from left to rig

Note: we will use 0 and 180 heading to determine the max tension and max offset.

Note: Fatigue seastate conditions to be finalized.

2.4 Simulation Software

The chosen software for this project is Orcaflex, a time-domain multibody hydrodynamics simulator developed by Orcina, Ltd., optimized for simulation of floating bodies connected by solid structures and lines. In this software a mathematical model of a real-life system is created with inter-connected components. The components of interest are the floater (semi-submersible), the turbine (blades, nacelle, tower), and the mooring lines. The system is input via a series of input files that contain information about the geometry and inertia properties. OrcaFlex can import hydrodynamic databases generated by a panel code (also called potential flow code). These codes can create a large database containing the complex coefficients that predict the pressure/flow interactions between pairs of panels in the input mesh, or between open ocean flow and panels in the input mesh. The software models the dynamic behavior of mooring lines, ropes, chains, umbilicals, and pipes using a one-dimensional finite element scheme. Each line is segmented into a series of nodes connected by massless segments, shown in Figure 8. The segments contain axial, bending, and (optionally) torsional stiffness and damping, and nodes contain mass and buoyancy information. The system is represented by a large set of coupled non-linear equations that describe the motion of the water and resulting forces on the individual masses, the motion of each mass, the fluid drag as the mass moves through the water, and the added mass of water that moves with the masses. Calculation of dynamic line behavior is done in five stages:

1. Calculation of tension forces from axial stiffness and damping contributions.

2. Calculation of bending moments at each node.

3. Calculation of shear forces at each node.

4. Calculation of torsional moments at each node.

5. Application of mass, drag, added mass, buoyancy, and wave effects (modeled using Morison's Equation), and calculation of total load at each node.

The ultimate goal of the statics calculation in OrcaFlex is to find positions and orientations for each element in the model such that all forces and moments are in equilibrium. Calculating statics requires an iterative approach using the multi-dimensional form of Newton's method.

3 Results and Discussion

Simulations with the synthetic mooring system involved runs to identify system characteristics, including natural periods, damping ratios, as well as stiffness properties. These are presented in detail and discussed in Sharman et al. (2022). This report presents results from simulations focused on the performance of the floater and mooring system in two design load cases (DLC) and one survival load case (SLC), see Table 5. The results in this section were processed as follows:

- Running one or more 1-hour simulations using the appropriate environmental conditions
- Concatenating the simulation data if multiple simulations were run
- Using OrcaFlex to calculate the peaks (or troughs depending on the data type)
- Selecting the top 10% of the peaks by magnitude
- Fitting a Weibull distribution to the top 10% of the peaks
- Using the Weibull distributions to predict the 95% most likely peak in a 3-hour storm

3.1 Performance in DLC 1.6, 6.1 and SLC I.1

For each of the three DLC conditions, charts were created to display the 95% peak surge offsets, pitch angles and line tensions. These results are presented as bar charts corresponding to 3-, 2- and 1-line cases for 60m WD and for 2- and 1-line cases for the 100 m WD. The wind direction is either at 0 or 180 deg, denoted by the nacelle orientation corresponding to the wind direction.

For the DLC 1.6 condition (Figure 3), the results show that the maximum surge offset is highest when the floater has one line per column and wind heading in 180 deg, irrespective of water depth. The pitch motion is rather similar between 7 – 8 deg when the wind is in the 0 deg condition. The line tensions are similar between 60 and 100 m WD, with the latter showing higher value when the nacelle has no yaw.

When the turbine is parked (DLC 6.1, Figure 4), the trends are similar with surge offset. Pitch values are fairly constant across all configurations tested, with the yawed nacelle consistently showing lesser values. The maximum line tension is seen in the 60m WD case.

In the survival storm condition (SLC I.1), we note that maximum tension occurs when we have a single line per column, Figure 5. Irrespective of the water depth, the maximum tension hovers between 7000 to 8000 kN. Max surge offset is about 20m for 60 m water depth (about 35%) and 22 m for 100m WD (21%). Maximum pitch values are 9 deg or less, with lesser pitch recorded for the 1-line case.

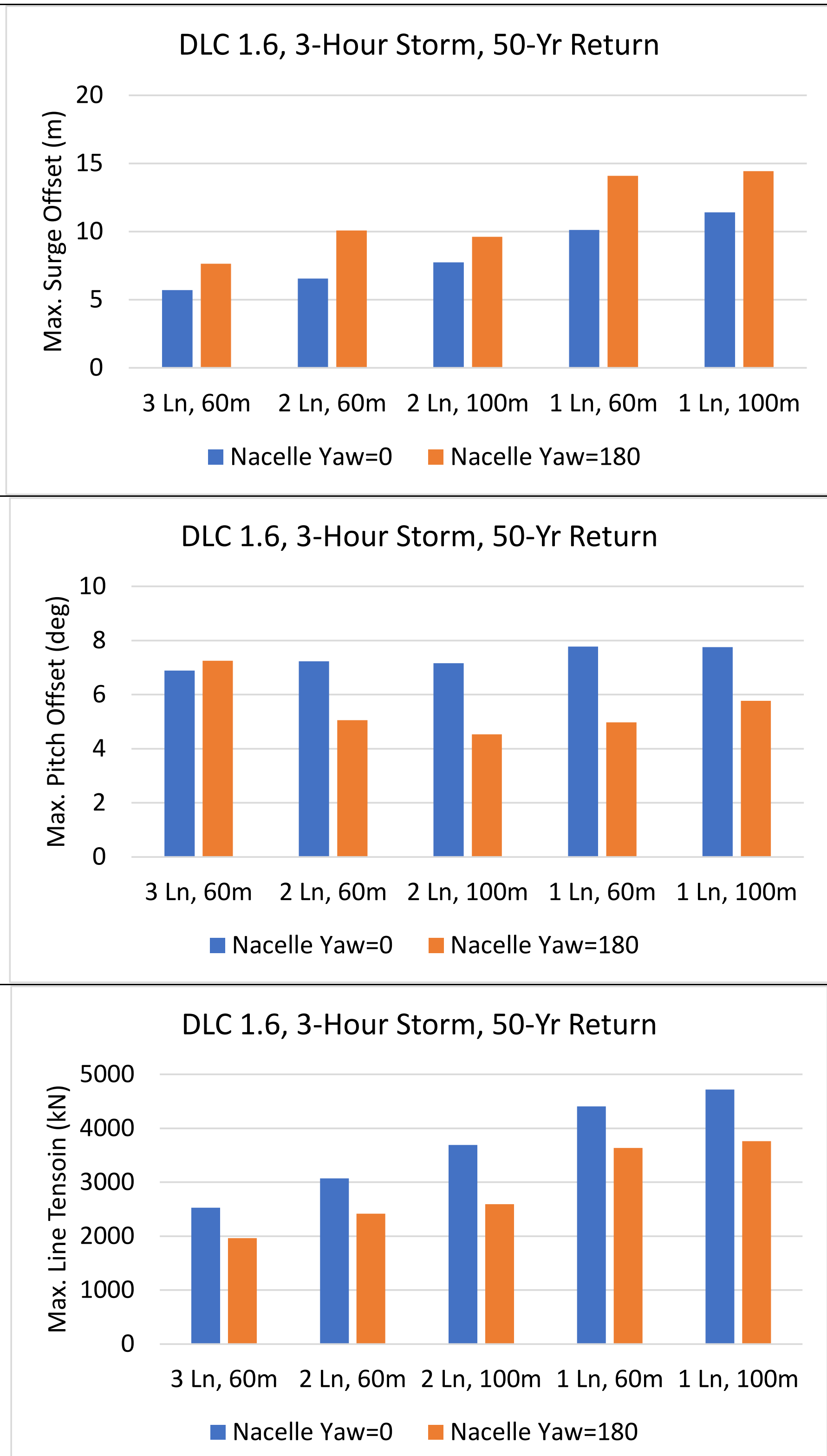

Figure 3. Simulation results at DLC 1.6 Operating Wind, and storm conditions corresponding to a 50-yr return period. Top: Max surge offset, Middle: max pitch offset and Bottom: max. line tension.

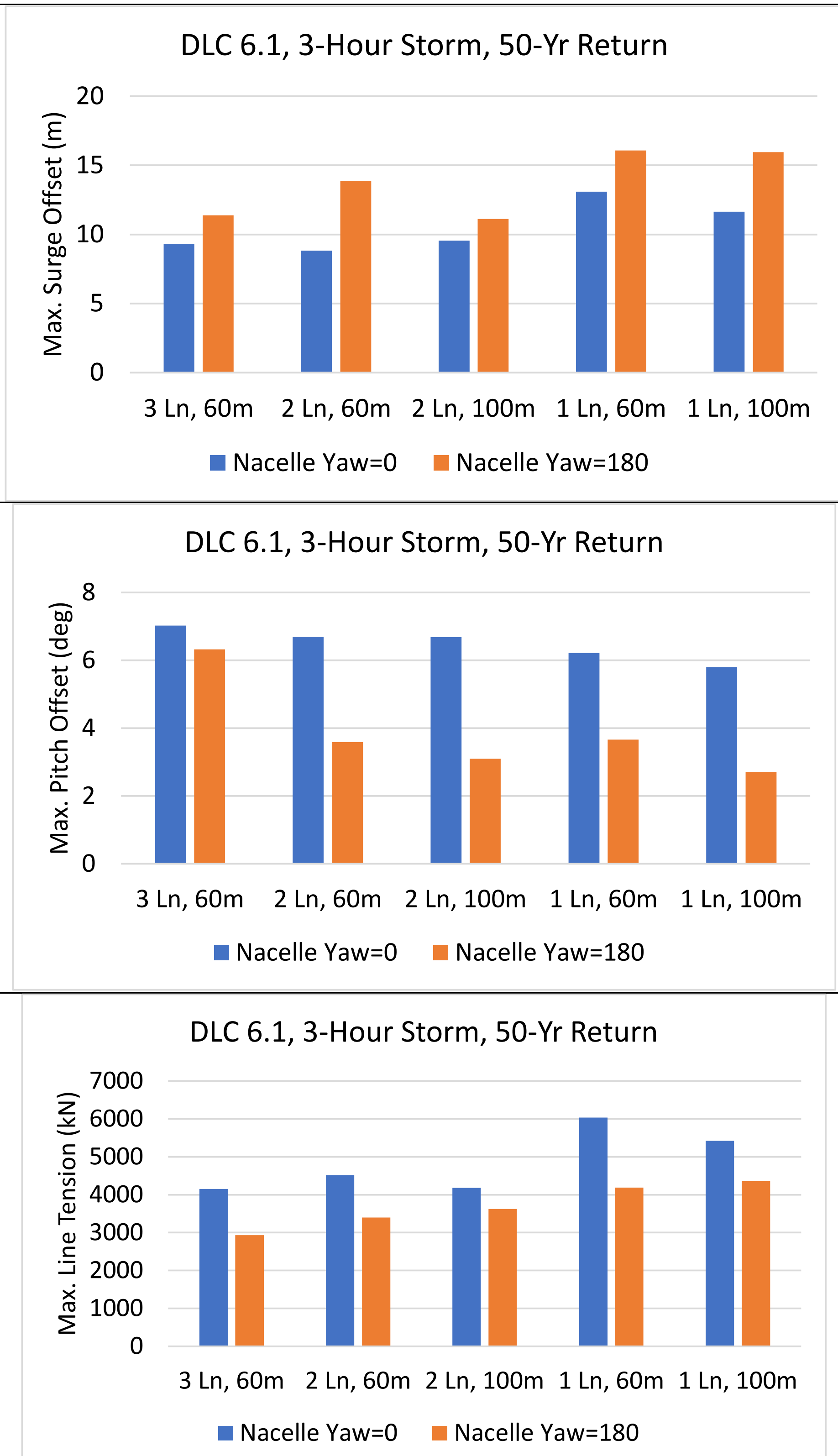

Figure 4 Simulation results at DLC 6.1 Parked turbine, and storm conditions corresponding to a 50-yr return period. Top: Max surge offset, Middle: max pitch offset and Bottom: max. line tension.

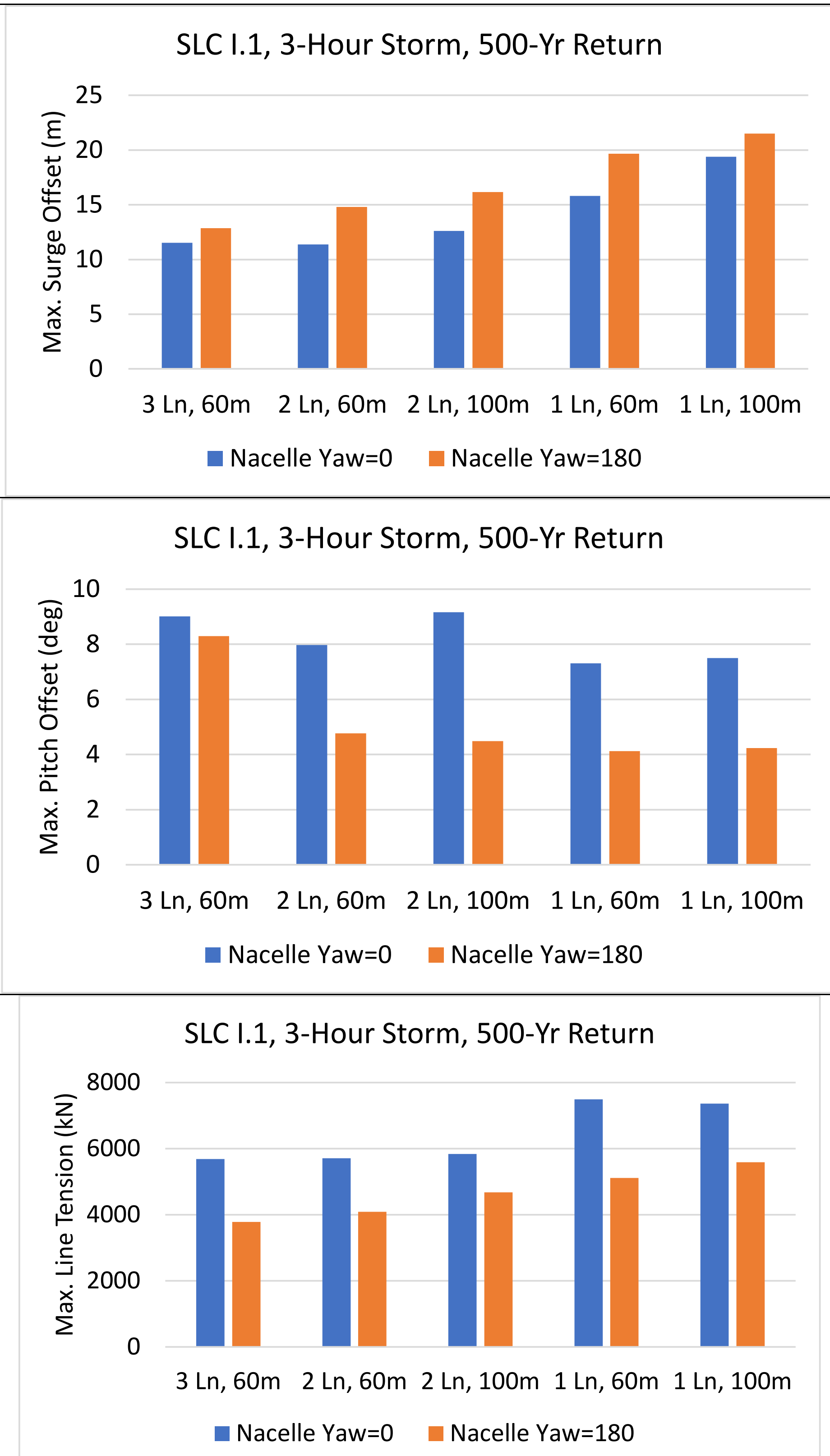

Figure 5 Simulation results at SLC I.1 Survival conditions corresponding to a 500-yr return period. Top: Max surge offset, Middle: max pitch offset and Bottom: max. line tension.

3.2 Factors of Safety

The factor of safety for a mooring line component is defined as the Maximum Tension divided by the Mean Breaking Load (MBL). The MBL values for each component in the two mooring systems that were simulated are listed in Table 6. A Factor of Safety can be calculated for a static analysis or a dynamic analysis. In the former, line tension is dictated by the fixed conditions, whereas in the latter, the maximum line tension is analyzed with simulation and extrapolation with a Weibull distribution. Factors of Safety for the three dynamic conditions considered in this analysis (DLC 1.6, DLC 6.1, and SLC I.1) are shown in Figure 20. The minimum Factor of Safety for the dynamic conditions is 2.38. Conditions for this are Survival Case SLC I.1, 60m water depth, and only one line per pontoon.

Table 6. Mean Breaking Load (kN) for each mooring line component

	Size	**MBL (kN)**
Config A (all chain, 3-lines/column)		
(All Chain)	180mm	21,387
Mixed Chain/Polyester Rope		
Platform Chain	160mm	17,811
Heavy Chain	210mm	29,110
Polyester Rope	240mm	17,790
Bottom/Anchor Chain	160mm	17,811

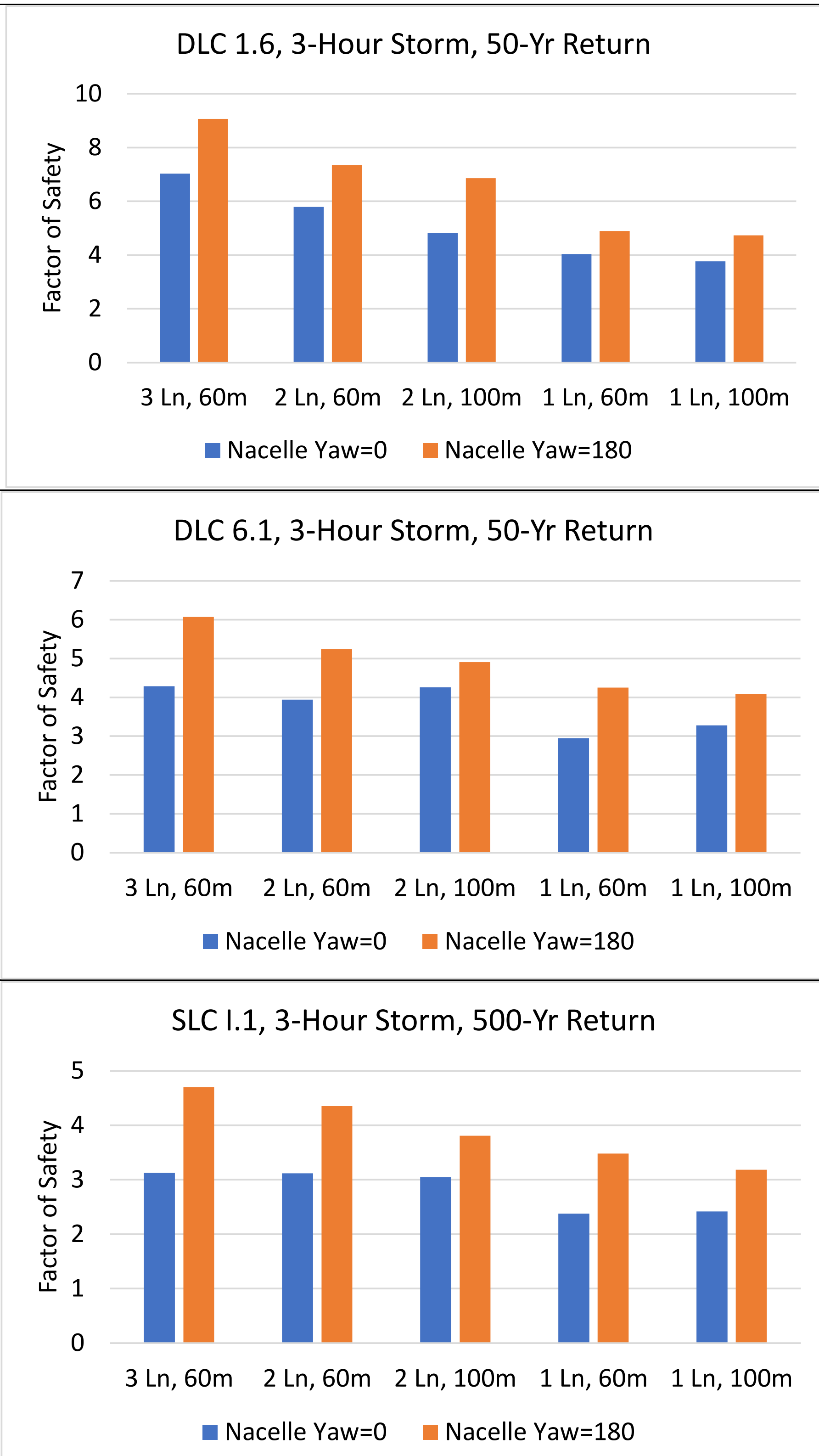

Figure 6 Factors of Safety for polyethylene line segment in mooring lines. Conditions: DLC 1.6 Operating turbine (50-yr return), DLC 6.1 Parked turbine (50-yr return), and SLC I.1 (500-yr) Parked turbine.

3.3 Fatigue analysis

Abbreviated fatigue analyses were performed on the mooring configurations that include polyester rope, in both 60m and 100m water depths. The exposure duration was assumed to be 25 years, or 219,144 hours including leap days. Based on data available from Carroll (2015) and Dunwoodie (2015), a representative value of 25% is chosen for downtime. In a 25-year exposure, it is likely that the floating wind turbine will be exposed to extreme hurricane conditions, so one hour of the survival condition SLC I.1 reasonably can be expected. The complete fatigue analysis assumes exposure conditions are listed in Table 7.

The analysis of mooring line tension-tension fatigue damage is calculated using the T-N curves per the following formula:

$$N * R^M = K$$

where:

N = Number of cycles

R = Ratio of tension range (double amplitude) to reference breaking strength (RBS)

M and K values are fatigue parameters (see Table 9)

Results of the fatigue analyses in 100m water are shown in Figure 7 and Figure 8, while those for the 60 m WD are shown in Figure 9 and Figure 10. Our analysis shows that for both water depths, the 2-line configuration will likely not fail within the lifetime of the structure. On the other hand, with a one-line configuration, the chains will likely fail ahead of the rope segment. The behavior across the water depths is similar, but the 100 m water depth seems more onerous due to the environmental conditions that prevail there.

Table 7. Simulation conditions used for fatigue analyses.

Condition	Description	Hours	Percent
DLC 1.6	Moderate operating condition	164,357	75.00%
DLC 6.1	Extreme conditions, rotor in “parked configuration” (downtime)	54,786	25.00%
SLC I.1	Survival condition (hurricane)	1	0.0005%
	Total	219,144 (25 years)	100.00%

Table 8. Suggested fatigue parameters from API RP-2SK

Component	T-N Curve Fatigue Parameters (API, ABS)	
	M	K
Polyester Rope (ABS)	5.2	25,000
Common Studless Chain (API)	3	316
Common Studlink Chain (API)	3	1,000

Table 9. Mean Breaking Strengths for studless chain and polyester rope used in the fatigue analyses.

Description	Size (mm)	Mean Breaking Strength (kN)
Platform Chain and Anchor Chain	160	17,811
Heavy Chain	210	29,110
Polyester Rope	240	17,790

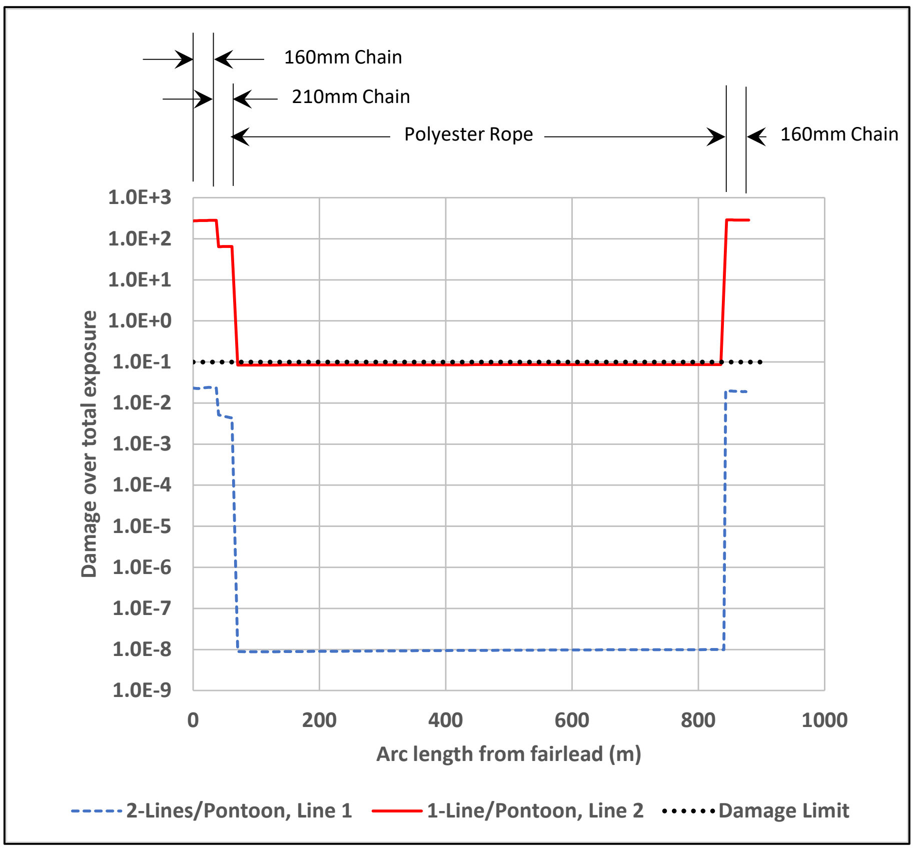

Figure 7 Fatigue damage to high-load mooring lines in 100m water. Extreme damage limit is 10% of total damage. Damage to all components in “2-Lines” configuration is acceptable, whereas the chain components are predicted to fail in the “1-Line” configuration

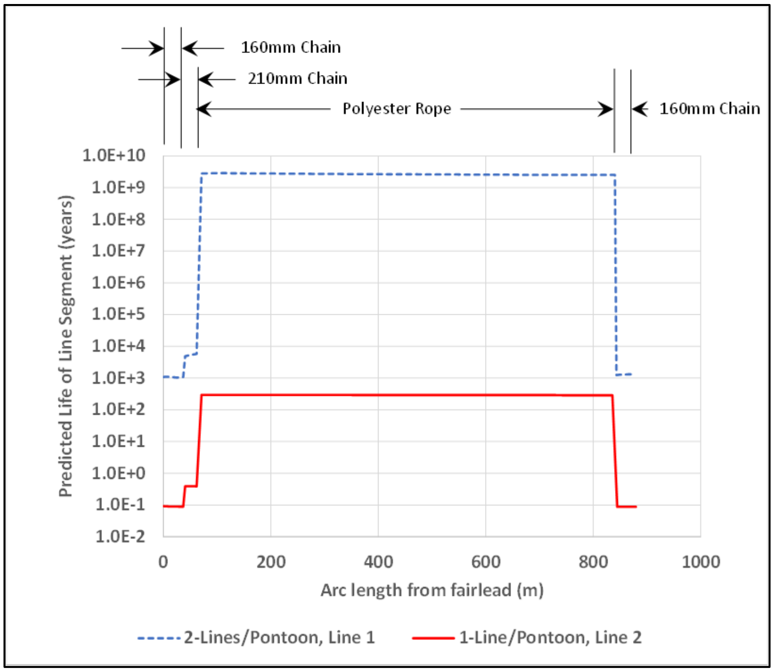

Figure 8 Projected life of individual components in mooring lines, 100m water depth. Polyester line has long lifetime in either configuration, while chain life is much shorter

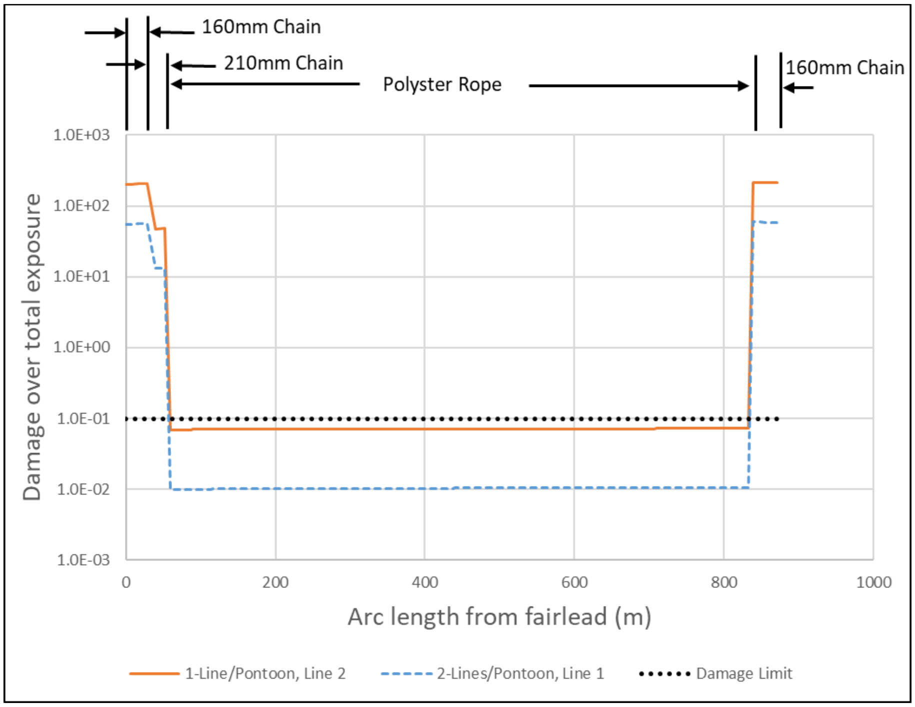

Figure 9 Fatigue damage to high-load mooring lines in 60m water. Extreme damage limit is 10% of total damage

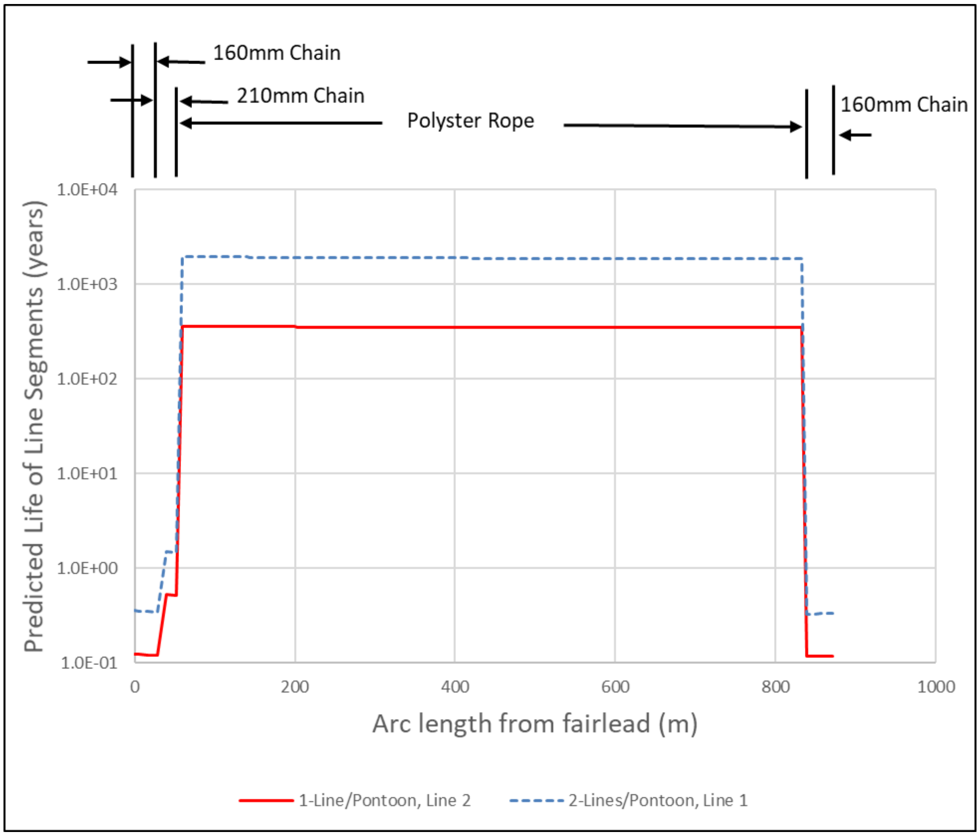

Figure 10 Projected life of individual components in mooring lines, 60m water depth. Polyester line has long lifetime in either configuration, while chain life is much shorter

3.4 Cost analysis

Based on material cost of the chain-heavy chain-polyester-chain system, the cost results per mooring line for 60m WD and 100m WD are shown in Table 10 and Table 11 respectively. It should be noted that having multiple chain sizes for small projects would result in higher costs due to the qualification process for each size of chain. This extra cost would be negligible for larger wind farms where the qualification costs would be spread to multiple units.

There are a wide variety of mooring connectors available on the market and all offer their own benefits to the project based on the type of mooring system that is chosen and the global performance requirements of the system. Costs for the connectors was not estimated for this report as they vary greatly and need to be chosen specifically for the project based on the overall needs of the project.

Table 10. Cost of Mooring Line for 60m Water Depth

Line Segment	Diameter (mm)	Static EA (kN)	Dynamic EA (kN)	MBL (kN)	Dry Weight (kg/m)	Wet Weight (kg/m)	Length (m)	Grade	Cost (USD) / Mooring Line
Platform Chain	160	1914000	NA	17811	512	445	34	R3	$61,446
Heavy Chain	210	3740000	NA	26749	883	768.21	24	R3	$67,377
Polyester Rope	240	204600	533800	17790	41.31	11.19	776		$170,067
Anchor Chain	160	1914000	NA	17811	512	445	37	R3	$66,868
TOTAL COST FOR EACH ML									**$365,758**

Table 11. Cost of Mooring Line for 100m Water Depth

Line Segment	Diameter (mm)	Static EA (kN)	Dynamic EA (kN)	MBL (kN)	Dry Weight (kg/m)	Wet Weight (kg/m)	Length (m)	Grade	Cost (USD) / Mooring Line
Platform Chain	160	1914000	NA	17811	512	445	39	R3	$70,482
Heavy Chain	210	3740000	NA	26749	883	768.21	24	R3	$67,377
Polyester Rope	240	204600	533800	17790	41.31	11.19	776		$170,067
Anchor Chain	160	1914000	NA	17811	512	445	37	R3	$66,868
TOTAL COST FOR EACH ML									**$374,794**

4 Conclusions

The project's scope was to conduct a feasibility study of developing a mooring system for an offshore wind turbine located in shallow waters off the US East Coast. Based on available data, we chose suitable sites and environmental conditions typical for two water depths – 60m and 100 m. For these two sites, we sized a semi-submersible and developed a conventional mooring system as well as a novel composite system comprising of chains and synthetic lines. The chosen mooring system is made up of chain, heavy chain and polyester. The advantages of this system are:

- Polyester rope is well proven mooring line component
- Mooring system footprint is similar to chain mooring system with clump weight
- Mooring performance meets strength criteria
- Heavy chain segment can reduce polyester rope size
- Better fatigue performance expected compared to the Chain-Polyester Rope-Chain mooring system.

We considered the number of lines per column as a variable that ranged from 1 – 3. We conducted simulations on the performance of the two mooring systems in various operating and survival conditions. The platform and mooring system performance in various operating and survival seastates were studied to assess the motion and tension characteristics of the system. This was followed by a fatigue analysis on the mooring lines.

Following are the significant findings.

1. For the DLC 1.6 operating condition, the results show that the maximum surge offset is highest when the floater has one line per column and wind heading in 180 deg, irrespective of water depth. The pitch motion is rather similar between 7 – 8 deg when the wind is in the 0 deg condition. The line tensions are similar between 60 and 100 m WD, with the latter showing higher value when the nacelle has no yaw.

2. When the turbine is parked (DLC 6.1), the trends are similar with surge offset as seen in DLC 1.6. Pitch values are fairly constant across all configurations tested, with the yawed nacelle consistently showing lesser values. The maximum line tension is seen in the 60m WD case.

3. In the survival storm condition (SLC I.1), we note that maximum tension occurs when we have a single line per column. Irrespective of the water depth, the maximum tension hovers between 7000 to 8000 kN. Max surge offset is about 20m for 60 m water depth (about 35%) and 22 m for 100m WD (21%). Maximum pitch values are 9 deg or less, with lesser pitch recorded for the 1-line case.

4. The minimum Factor of Safety for the dynamic conditions is 2.38. Conditions for this are Survival Case SLC I.1, 60m water depth, and only one line per pontoon.
5. Abbreviated fatigue analyses were performed on the mooring configurations for a 25-year exposure duration, in both 60m and 100m water depths. Our analysis shows that for both water depths, the 2-line configuration will likely not fail within the lifetime of the structure. On the other hand, with a one-line configuration, the chains will likely fail ahead of the rope segment. The behavior across the water depths is similar, but the 100 m water depth seems more onerous due to the environmental conditions that prevail there.

The cost analysis shows that the synthetic rope system has lower material cost, almost 14 times lower than the all-chain mooring system. The use of the synthetic rope also greatly reduces the installation costs (three times cheaper than chain) as the storage of the product on the deck, or in a carousel, enables the vessel to carry more mooring lines at one time, and reduces costs associated with transits. Also, having to break the long chain segments to fit the chosen installation vessel's chain lockers will require additional connectors, adding to the cost of the mooring lines and the time to connect them during installation. This exercise further enforces the selection of a chain-synthetic-chain mooring system.

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