Project #154632: Innovative Anchoring System for Floating Offshore Wind

Final Report

Prepared for:

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Acronyms and Abbreviations

ABS	American Bureau of Shipping
API	American Petroleum Institute
BOEM	Bureau of Ocean Energy Management
DEG	Degrees
DLC	Design Load Case
DNV	Det Norske Veritas
FOWT	Floating offshore wind turbines
IEC	International Electrotechnical Commission
Kn	Kilonewtons
NOAA	National Oceanic and Atmospheric Administration
NTQ	New Technology Qualification
OSW	Offshore wind
SLC	Survival Load Case
St Dev	Standard Deviation
WWC	Wind wave current

Executive Summary

Traditional anchoring systems use large heavy weights, caissons, driven piles, or drag embedment anchors to achieve the high-pullout forces required for wind turbine moorings. High weights and forces ultimately convert into high costs that result in an anchoring contribution of 10-16% to levelized cost of energy (LCOE) for floating wind. Triton is developing its anchor system to address these challenges.

During this program, Triton was contracted to develop a pilot-scale anchor prototype for demonstration through the American Bureau of Shipping (ABS) New Technology Qualification (NTQ) Process. Triton's main objective was to conduct anchor capacity testing and receive an ABS Type Approval at the end of the Prototype Validation Stage of the NTQ process. These engineering tests are crucial to adoption of the anchor technology.

Triton enlisted the support of the University of Rhode Island to perform work in the geotechnical research and analyses, the University of Massachusetts at Amherst to develop mooring loads for catenary, taut, and shared mooring conditions, and ABS to support the NTQ process. Helical Drilling assisted the team with helical pile installation and load testing.

During the program, Triton completed the following primary tasks:

- FEAMooring FAST Analysis
- ABS NTQ Progression through the System Integration Stage

This report summarizes the findings and completion of these tasks.

1 FEAMooring FAST Analysis

The Anchor Loading Assessment was performed in partnership with the University of Massachusetts in Amherst. This section details the analysis and findings.

1.1 Environmental Conditions

This section describes the environmental conditions, wind speed, wave height and current, used in floating offshore wind turbine simulations to determine appropriate load values for anchor design and analysis. Load cases and environmental conditions are based on current IEC documents (61400-1, 61400-3-1, 61400-3-2), an ABS's Guide for Building and Classing Floating Offshore Wind Turbine Installations, and a recent BOEM report prepared by DNV-GL (100396...63-HOU-01, BOEM 2018-057).

Conditions are reported for a selection of sites along the US Atlantic and Pacific coasts.

1.1.1 Environmental Conditions Reported

Three environmental conditions are reported here: mean hub height wind speed based on a 10-min averaging window, significant wave height and peak spectral period based on a 1-hour or 3-hour averaging window, and mean current speed. Raw data, as obtained from, for example, the NOAA data buoy center, may be based on different averaging windows or, in the case of wind speed, reported at an elevation different from the hub height. Commonly accepted practices have been used to convert data for elevation and averaging windows, as stated above, when appropriate.

Other environmental conditions such as tides, storm surge, marine growth, wave spreading, sea ice, etc. are not included in this report.

1.1.2 Design Load Cases

A full loads analysis for real-world design and construction required the analysis of dozens of design load cases (DLCs) and thousands to tens of thousands of simulations. This report includes conditions corresponding to three design load cases as specified in IEC 61400-3-1 and as defined in Table 1.

Table 1. Design load cases considered

Load Case	Wind speed	Sig. Wave Height	Wave Period	Current	Safety Factor
DLC 1.6 (Operating)	Rated / max thrust	50 year conditioned on wind speed	50 year conditioned on wind speed	Normal Current Model	1.35
DLC 6.1 (Parked / Idling)	50 year	50 year	50 year	Extreme Current Model (50 year)	1.35
SLC / DLC I.1 (Survival)	500 year	500 year	500 year	50 year	1.0

These three load cases are chosen to cover an operating case (DLC 1.6) in which wind loads are expected to be maximum due to the maximum thrust generated by the rotor, a non-operating case (DLC 6.1) with extreme wind and wave conditions but with the turbine parked and feathered or idling, and a survival load case (SLC) corresponding to a 500 year event, but with a lower partial safety factor. The SLC check is intended to provide sufficient probability of survival for extreme events such as hurricanes. For the purposes of this study wind/wave misalignment and yaw misalignment are neglected and DLC 1.6 is evaluated at rated wind speed (maximum thrust) rather than across all operating wind speeds.

1.1.3 Selected Sites

Sites have been selected to provide a broad representation of conditions likely to prevail for US OSW developments (Table 2). Other considerations are the site water depth and the availability of publicly available metocean data for site condition determination. The record lengths range from 27 to 38 years and it should, therefore, be noted that the estimates for 50 and, particularly, 500-year events should be used with caution for anything more than conceptual design or proof-of-concept analysis. Record lengths include only those years in which valid data was recorded for more than 50% of the year. Table 2 shows a variety of sites across the United States that are of relative interest because they are close to potential US floating wind sites.

Table 2. Metocean sites

Site name	Location	Water depth (m)	Simulation water depth (m)	Data source	Duration (wave/wind in yrs.)
Monhegan Island	43.750 N 69.300 W Gulf of Maine, ME	100	200	Purpose-deployed buoy (Dagher et al. 2017)	3 / 3
Nantucket	40.504 N 69.248 W 54 NM SE of Nantucket, MA	74.7	150	NOAA data buoy 44008	35 / 32
Virginia Beach	36.609 N 74.842 W 64 NM ESE of Va. Beach, VA	47	100	NOAA data buoy 44014	29 / 27
Stonewall Bank	44.669 N 124.546 W 20 NM W of Newport, OR	160	150	NOAA data buoy 46050	28 / 27
Santa Maria	34.956 N 121.019 W 21 NM NW of Pt. Arguello, CA	465	450	NOAA data buoy 46011	38 / 36

1.1.4 Environmental Conditions

Environmental conditions for the sites listed in Table 2 and the DLCs detailed in Table 1 are given, below, in Table 3. The peak spectral wave period (Tp) is calculated in accordance with API RP 2A-WSD and API Bulletin 2INTMET from the significant wave height (Hs):

$$T_p = 11.7\sqrt{\frac{H_s}{g}}$$

Where g = gravity. This is a lower bound estimate of the peak spectral period, which, in general, induces larger loads on the platform.

The current is calculated as 1% of the wind speed at the appropriate return period following IEC 61400-3- 1.

Table 3. Environmental Conditions

Site	Load case	Wind speed (m/s)	Wave height (m)	Wave period (s)	Current (m/s)
Monhegan					
	DLC 1.6	10.6	8.0	12.7	0.30
	DLC 6.1	40	10.2	14.1	0.45
	SLC / I.1	45	12.0	15.3	0.50
Nantucket					
	DLC 1.6	10.6	7.6	10.3	0.41
	DLC 6.1	40.8	11.5	12.7	0.45
	SLC / I.1	44.6	12.7	13.3	0.45
Virginia Beach					
	DLC 1.6	10.6	6.8	9.8	0.45
	DLC 6.1	45.1	8.8	11.1	0.57
	SLC / I.1	56.8	9.8	11.7	0.57
Stonewall Bank					
	DLC 1.6	10.6	9.3	11.4	0.37
	DLC 6.1	37.0	13.9	13.9	0.38
	SLC / I.1	38.3	16.6	15.2	0.38
Santa Maria					
	DLC 1.6	10.6	7.8	10.4	0.33
	DLC 6.1	32.5	9.2	11.3	0.37
	SLC / I.1	37.1	9.8	11.7	0.37

1.2 Anchor Loading Analysis

All of the example cases use the IEA 15MW turbine supported by a semi-submersible platform, with station-keeping provided by a semi-taut mooring system. Mooring lines use 100m of chain at the anchor end, 150m of chain at the fairlead end, and polyester rope for the middle section of the mooring lines. WWC directions of 0° and 60° are considered as are DLC 1.6, DLC 6.1 and SLC. The turbine spacing is 1,852 m (1 NM), the spacing selected for the Vineyard Wind project off the Massachusetts coast, except for the Monhegan Island site, for which a turbine spacing of 1,392 m is used, the spacing used at the Hywind Scotland project. Site specific parameters are given in each subsection

This section describes anchor loads generated by FOWT platforms on a shared anchor. Loads are generated using numerical simulations executed in FAST and the input environmental conditions are described in the accompanying report on environmental conditions. The coordinate system and line geometry used, corresponding to a three-line multiline anchor (small grey circle) and FOWTs (yellow circles) with three mooring lines, is shown in Figure 1. When single line anchor loads are reported they are reported for the critical mooring line, namely line 2 (red line), with Wind Wave Current (WWC) acting in the positive *x* direction corresponding to an WWC direction of 0°.

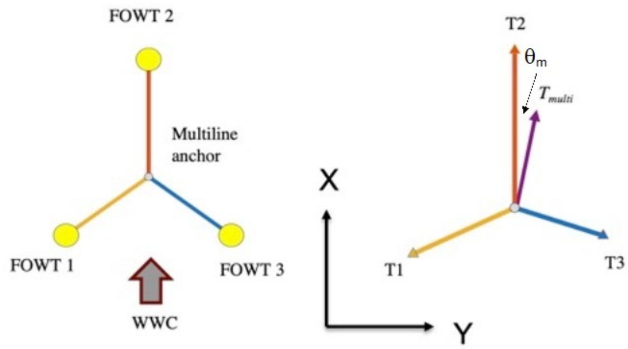


Figure 1. Mooring line geometry and coordinate systems.

1.2.5 Example Cases

1.2.5.1 Case 1: Monhegan Island

The water depth used for the MONHEGAN site is 200 m, roughly reflective of deeper water sites within the Gulf of Maine. The angle of inclination of the taut mooring lines—set by the turbine spacing and water depth—is 14.3°. The turbine spacing, for this case only, is 1,392 m.

Figure 2 shows one hour load time histories for the MONHEGAN site, SLC, as illustrative of the temporal variation of the loads. Table 4 shows the loads and load direction and inclination for the three load cases. SLC unfactored loads are largest, but DLC 6.1 would control after application of partial safety factors. The numerical results are taken from six 1-hour simulations and the maximum values are the average of the maximum value in each 1-hour simulation.

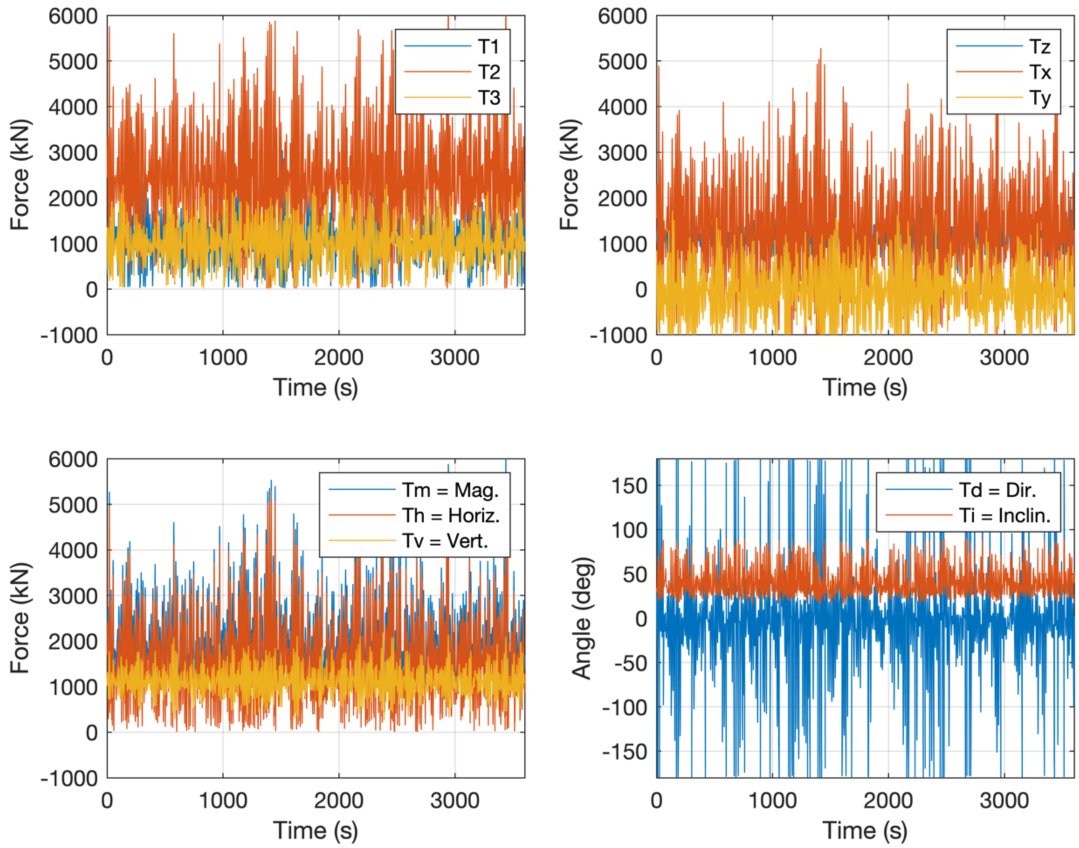


Figure 2. Example load time histories for SLC at Monhegan Island

Table 4. Load characteristics for MONHEGAN

a) Load characteristics for MONHEGAN, DLC 1.6. Unfactored loads, multiply by 1.35 for factored loads.

	0 degree WWC			60 degree WWC		
Value	**Maximum (kN)**	**Average (kN, deg)**	**Stdev. (kN, deg)**	**Maximum (kN)**	**Average (kN, deg)**	**Stdev. (kN, deg)**
Single line load	5500	3200	550	4100	2900	270
Multiline						
Magnitude	4800	2600	540	3800	2800	290
Horizontal	4500	2200	550	3400	2300	360
Vertical	1900	1300	160	2100	1600	120
Direction	N/A	0	8	N/A	60	8
Inclination	N/A	30	5	N/A	35	5

b) Load characteristics for Case 1, DLC 6.1. Unfactored loads, multiply by 1.35 for factored loads.

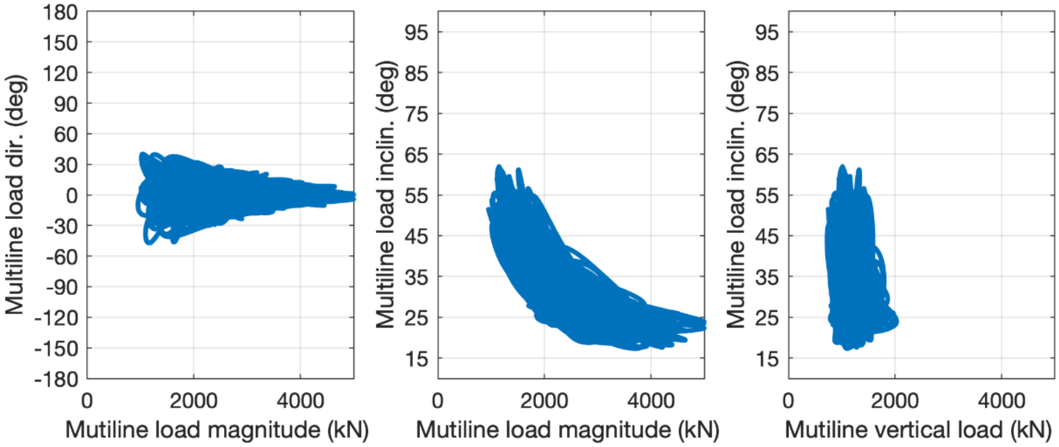
	0 degree WWC			60 degree WWC		
Value	**Maximum (kN)**	**Average (kN, deg)**	**Stdev. (kN, deg)**	**Maximum (kN)**	**Average (kN, deg)**	**Stdev. (kN, deg)**
Single line load	5700	2200	830	3700	2000	410
Multiline						
Magnitude	4800	1700	650	3200	1800	370
Horizontal	4200	1300	710	2900	1200	540
Vertical	2100	1100	240	1900	1200	190
Direction	N/A	0	50	N/A	60	40
Inclination	N/A	45	15	N/A	45	15

c) Load characteristics for MONHEGAN, SLC. Note that for SLC the partial safety factor is 1.0 and therefore factored and unfactored loads are identical

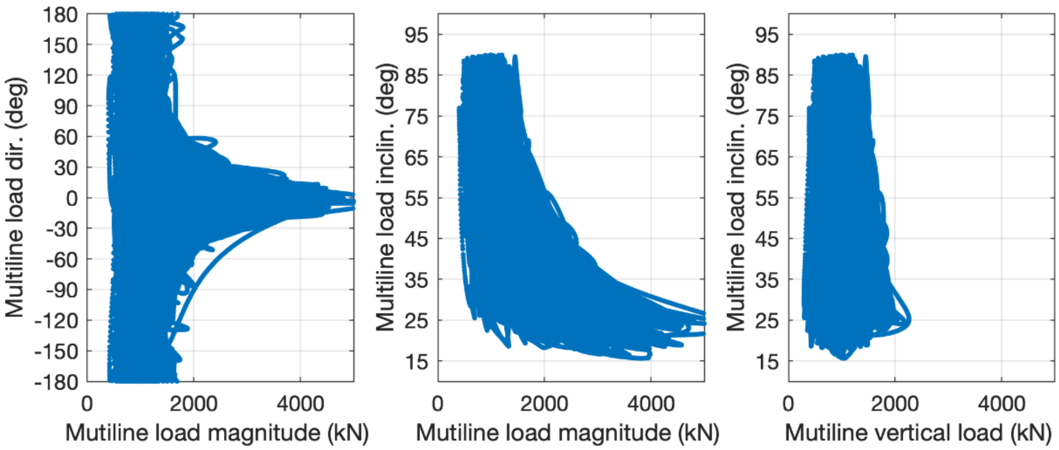
	0 degree WWC			60 degree WWC		
Value	**Maximum (kN)**	**Average (kN, deg)**	**Stdev. (kN, deg)**	**Maximum (kN)**	**Average (kN, deg)**	**Stdev. (kN, deg)**
Single line load	6800	2500	1100	4300	2200	530
Multiline						
Magnitude	6100	2000	880	3800	2100	480
Horizontal	5700	1600	930	3400	1500	630
Vertical	2400	1100	310	2100	1300	230
Direction	N/A	0	50	N/A	60	35
Inclination	N/A	40	15	N/A	40	15

There is an alternative way to look at the loads, which focusses on the combination of load magnitude and direction or inclination. Figure 3 shows a scatter plots of the multiline load direction and inclination against the magnitude and the vertical component of the load for each of the load cases. With the WWC direction at 0° the largest magnitude loadings occur aligned with the WWC direction, but load magnitudes of 25% of peak occur in directions of ±35° and 50% of peak in directions of ±20°. The directional variations occur even without any variation in the WWC direction.

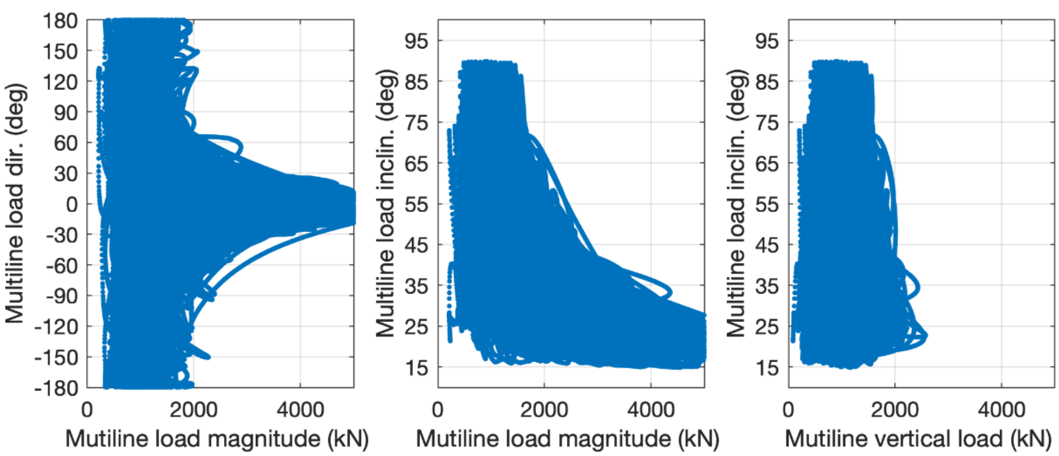
Multiline load inclination varies less than direction (Table 4), but the variation is associated with the corresponding load magnitude and may affect anchor capacity. Load magnitude is largest at small inclination angles of approximately 25° (the taut line attachment angle for this case is 14.3°) and decreases to approximately 30% of peak for inclination angles as high as 60°-70°. Vertical load on the anchor is, relatively, less variable with load inclination, indicating that increases in effective load inclination are driven by reduction in the horizontal component rather than increases in the vertical component of anchor load. Anchor capacity analysis should be performed to asses where along the magnitude-direction-inclination surface front the critical design point lies.



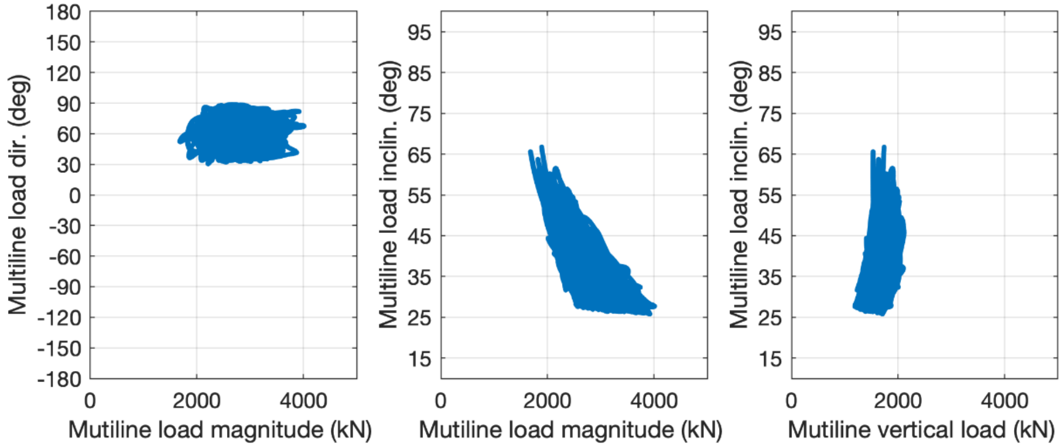
(a) DLC 1.6, unfactored (0°)



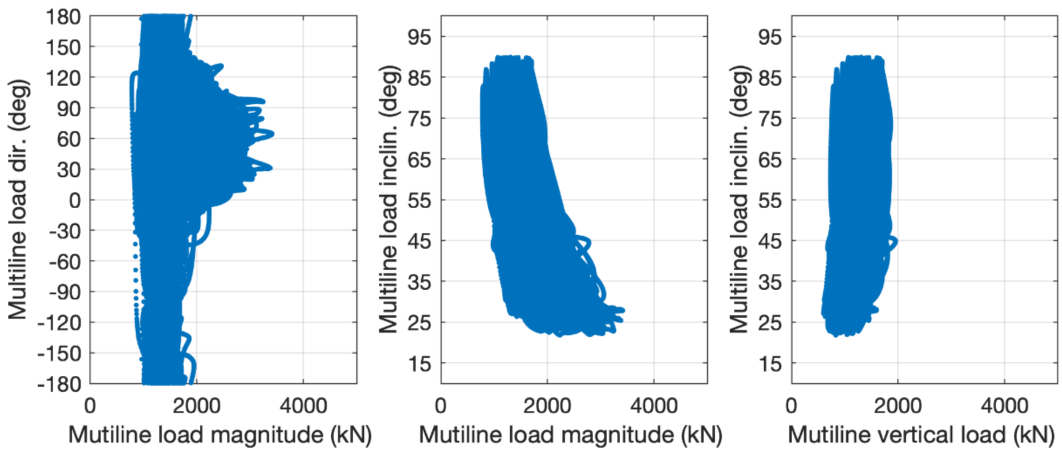
(b) DLC 6.1 unfactored (0°)



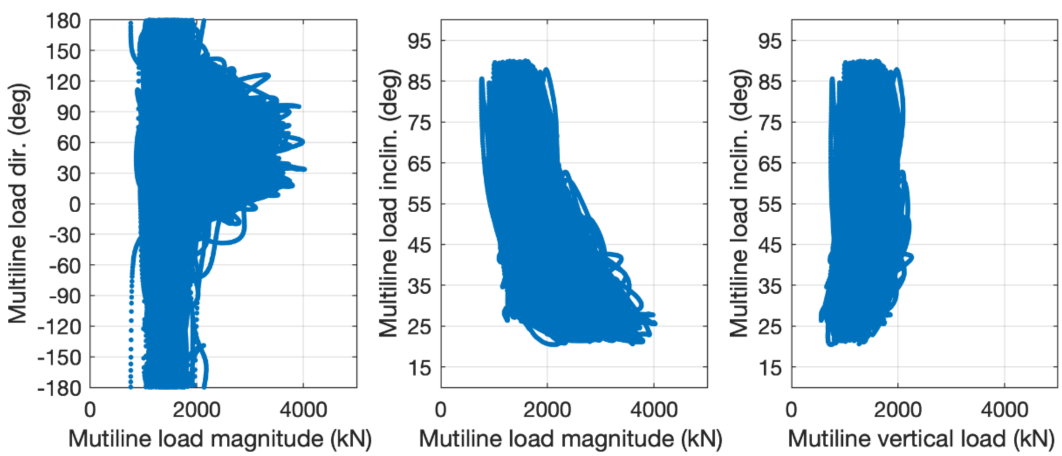
(c) SLC (0°)



(e) DLC 1.6, unfactored (60°)



(f) DLC 6.1 unfactored (60°)



(g) SLC (60°)

Figure 3. Relationship between multiline anchor load magnitude and vertical component and load direction and inclination for MONHEGAN. Loads shown are unfactored.

1.2.5.2 Case 2: Stonewall

At the STONEWALL site the turbine spacing is 1,852 m (1 NM) and the simulation water depth is 150 m, resulting in a taut angle of 7.9°.

Table 5. Load characteristics for STONEWALL

a) Load characteristics for STONEWALL, DLC 1.6. Unfactored loads, multiply by 1.35 for factored loads.

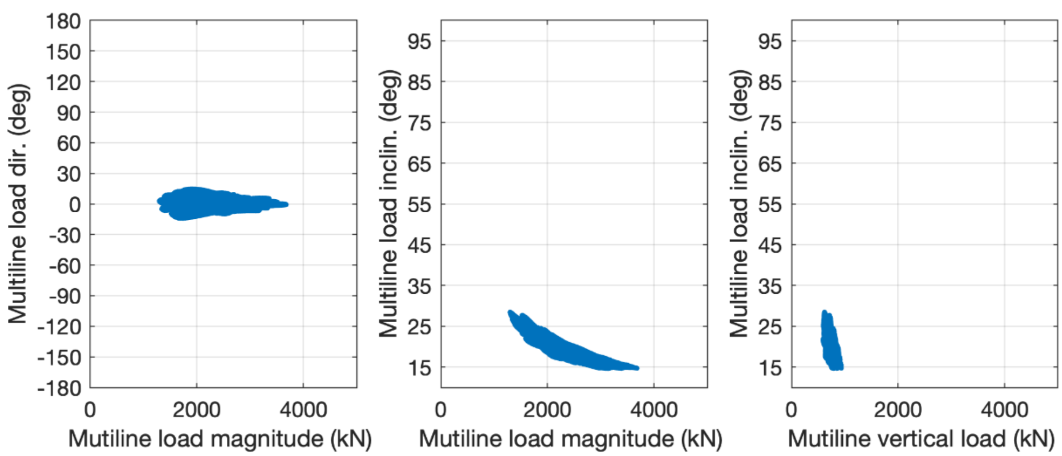
Value	0 degree WWC Maximum (kN)	Average (kN, deg)	Stdev. (kN, deg)	60 degree WWC Maximum (kN)	Average (kN, deg)	Stdev. (kN, deg)
Single line load	4900	3300	290	3200	2700	110
Multiline						
Magnitude	3500	2300	290	3000	2300	170
Horizontal	3400	2200	290	2900	2200	180
Vertical	930	760	40	960	820	30
Direction	N/A	0	3	N/A	60	5
Inclination	N/A	20	2	N/A	20	2

b) Load characteristics for STONEWALL, DLC 6.1. Unfactored loads, multiply by 1.35 for factored loads.

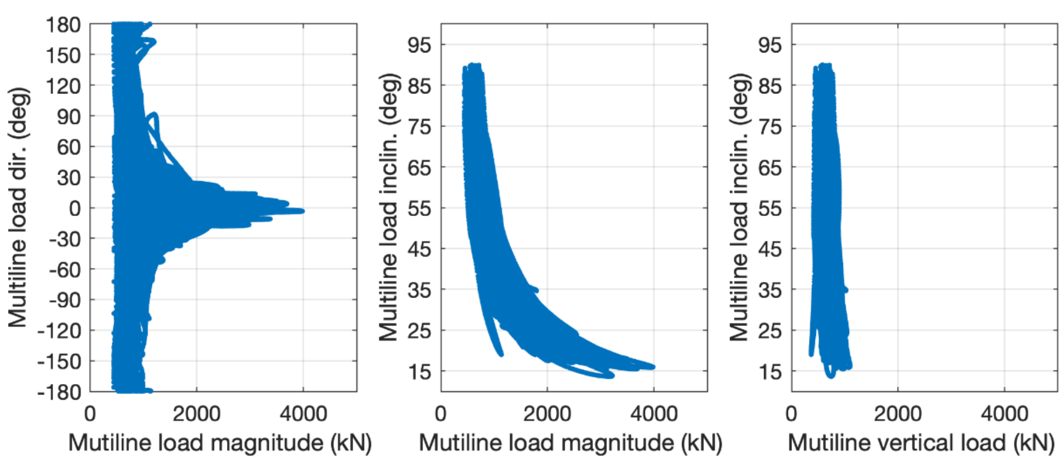
Value	0 degree WWC Maximum (kN)	Average (kN, deg)	Stdev. (kN, deg)	60 degree WWC Maximum (kN)	Average (kN, deg)	Stdev. (kN, deg)
Single line load	4800	2300	550	3100	2000	220
Multiline						
Magnitude	3600	1200	440	2400	1200	320
Horizontal	3400	930	510	2400	920	440
Vertical	1000	700	90	970	700	80
Direction	N/A	0	40	N/A	60	35
Inclination	N/A	40	15	N/A	40	15

c) Load characteristics for STONEWALL, SLC. Note that for SLC the partial safety factor is 1.0 and therefore factored and unfactored loads are identical

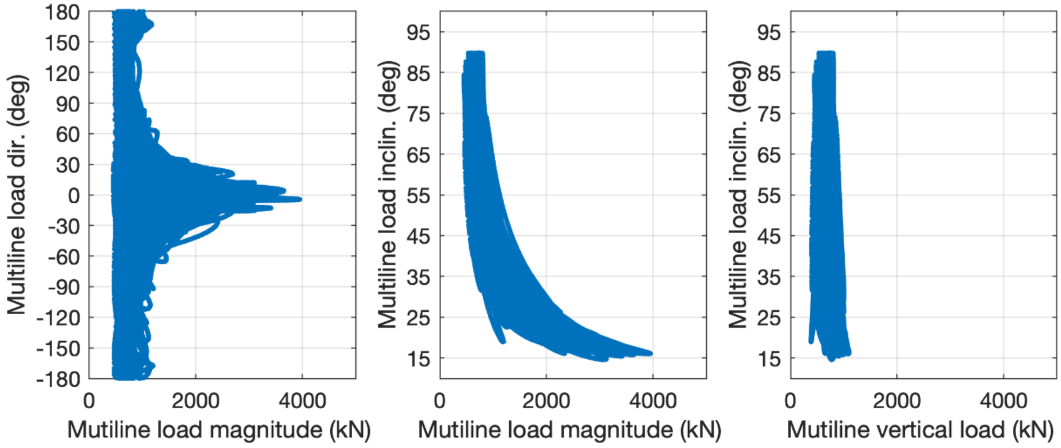
Value		**0 degree WWC**			**60 degree WWC**	
	Maximum (kN)	**Average (kN, deg)**	**Stdev. (kN, deg)**	**Maximum (kN)**	**Average (kN, deg)**	**Stdev. (kN, deg)**
Single line load	4800	2300	550	3100	2000	220
Multiline						
Magnitude	3600	1200	440	2500	1200	330
Horizontal	3400	930	510	2400	940	450
Vertical	1000	700	90	960	700	80
Direction	N/A	0	40	N/A	60	35
Inclination	N/A	40	15	N/A	40	15



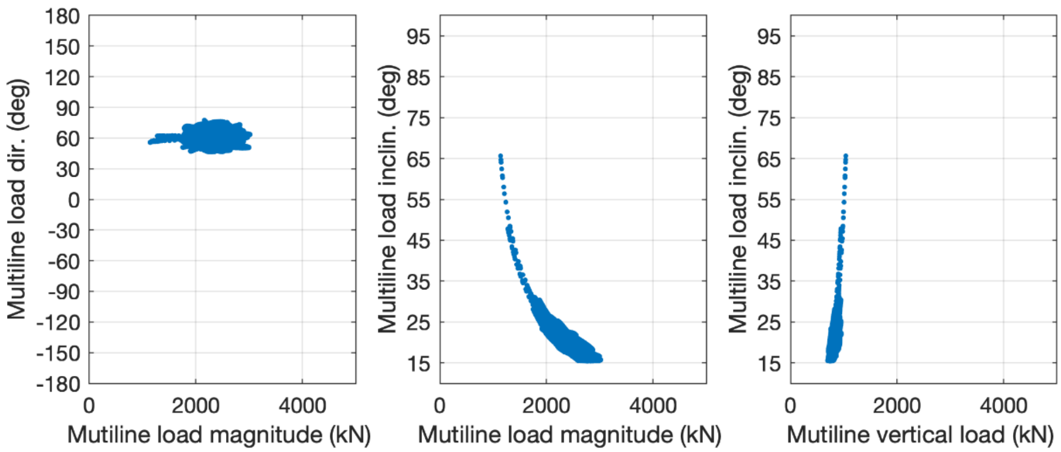
(a) DLC 1.6, unfactored (0°)



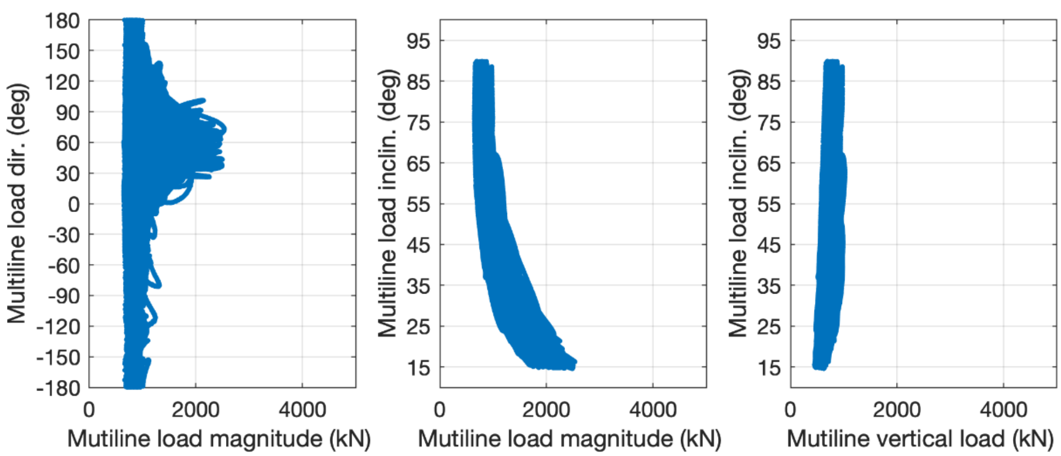
(b) DLC 6.1 unfactored (0°)



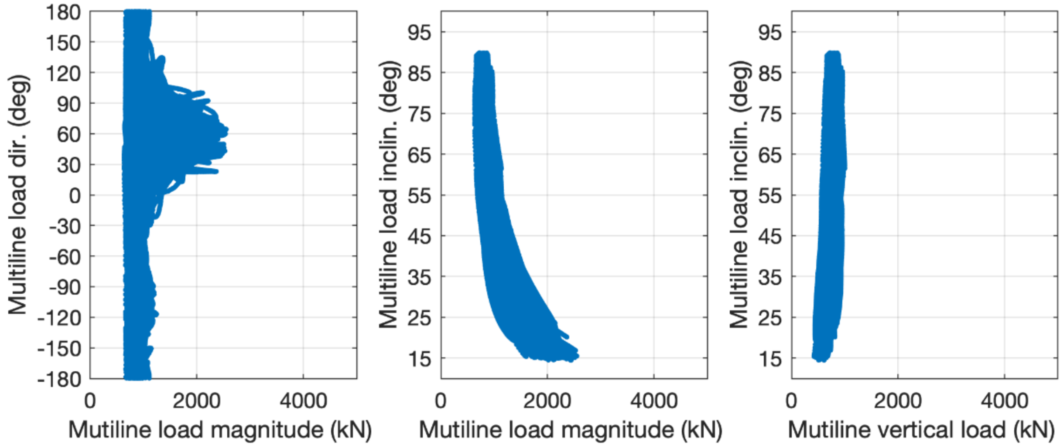
(c) SLC (0°)



(e) DLC 1.6, unfactored (60°)



(f) DLC 6.1 unfactored (60°)



(g) SLC (60°)

Figure 4. Relationship between multiline anchor load magnitude and vertical component and load direction and inclination for STONEWALL. Loads shown are unfactored.

1.2.5.3 Case 3: Nantucket

At the NANTUCKET site the turbine spacing is 1,852 m (1 NM) and the simulation water depth is 150 m, resulting in a taut angle of 7.4°.

Table 6. Load characteristics for NANTUCKET, DLC 1.6. Unfactored loads, multiply by 1.35 for factored loads.

a) Load characteristics for Nantucket, DLC 1.6. Unfactored loads, multiply by 1.35 for factored loads.

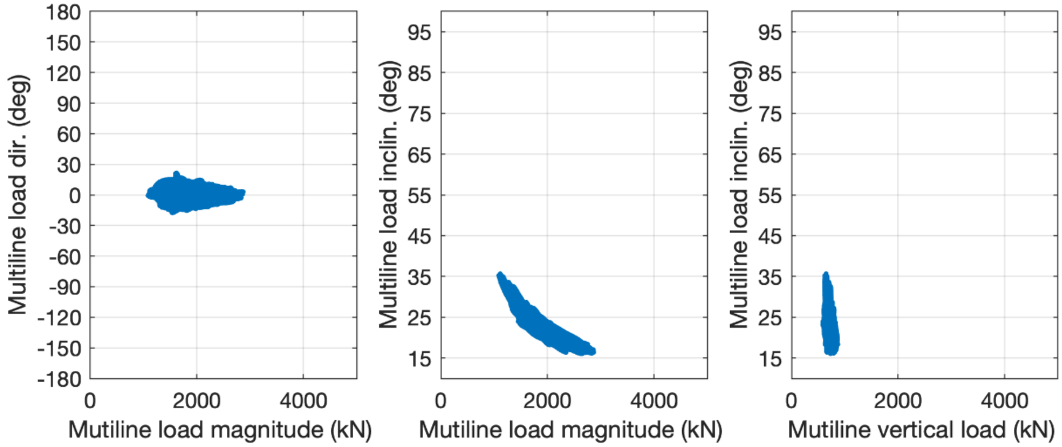
Value	**0 degree WWC**			**60 degree WWC**		
	Maximum (kN)	**Average (kN, deg)**	**Stdev. (kN, deg)**	**Maximum (kN)**	**Average (kN, deg)**	**Stdev. (kN, deg)**
Single line load	4000	3100	230	3000	2600	120
Multiline						
Magnitude	2800	1900	230	2500	1900	160
Horizontal	2700	1800	240	2400	1800	180
Vertical	850	720	35	860	750	30
Direction	N/A	0	5	N/A	60	5
Inclination	N/A	20	2.5	N/A	25	2.5

b) Load characteristics for Nantucket, DLC 6.1. Unfactored loads, multiply by 1.35 for factored loads.

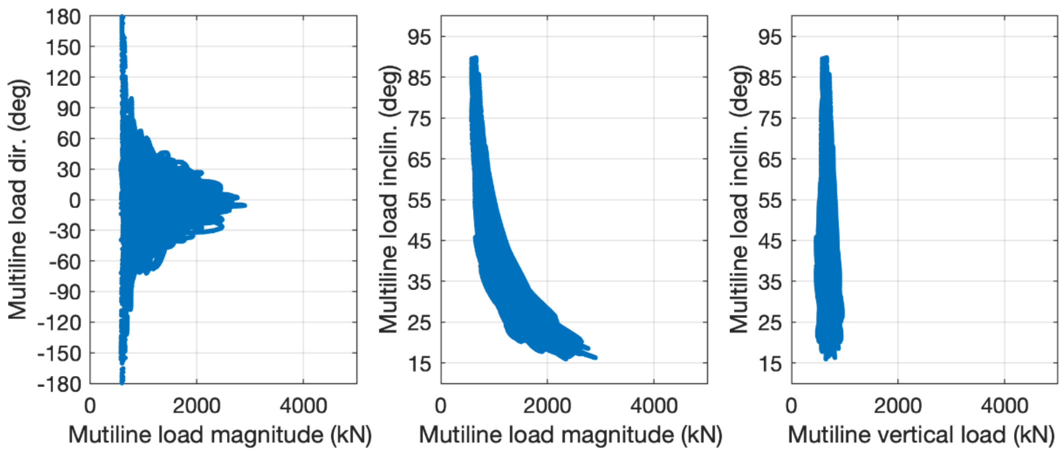
Value	0 degree WWC Maximum (kN)	Average (kN, deg)	Stdev. (kN, deg)	60 degree WWC Maximum (kN)	Average (kN, deg)	Stdev. (kN, deg)
Single line load	3900	2600	360	2900	2200	180
Multiline						
Magnitude	2700	1300	330	2300	1300	260
Horizontal	2500	1100	370	2200	1100	330
Vertical	910	690	60	890	700	50
Direction	N/A	0	15	N/A	60	15
Inclination	N/A	35	10	N/A	35	10

c) Load characteristics for Nantucket, SLC. Note that for SLC the partial safety factor is 1.0 and therefore factored and unfactored loads are identical

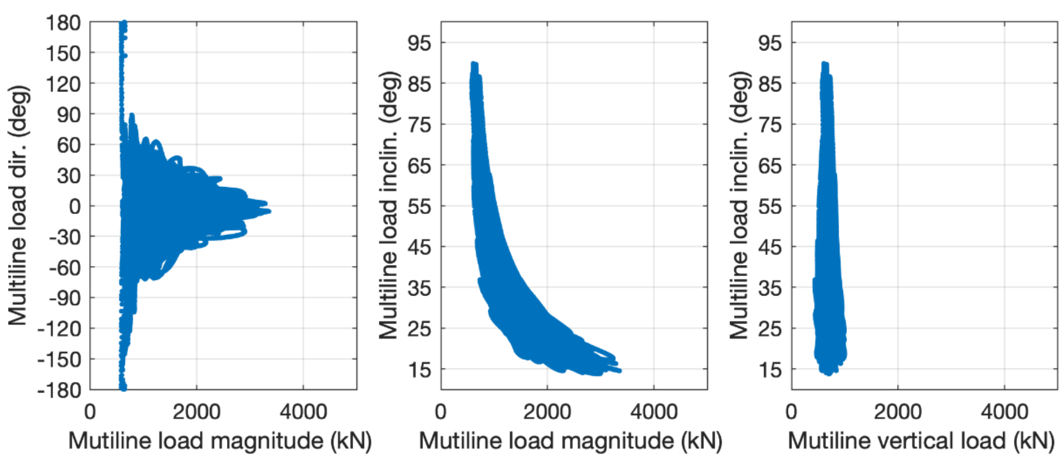
Value	0 degree WWC Maximum (kN)	Average (kN, deg)	Stdev. (kN, deg)	60 degree WWC Maximum (kN)	Average (kN, deg)	Stdev. (kN, deg)
Single line load	4300	2700	420	3200	2300	220
Multiline						
Magnitude	3100	1500	400	2600	1500	310
Horizontal	3000	1300	440	2500	1300	370
Vertical	950	700	70	930	710	60
Direction	N/A	0	15	N/A	60	10
Inclination	N/A	30	10	N/A	30	10



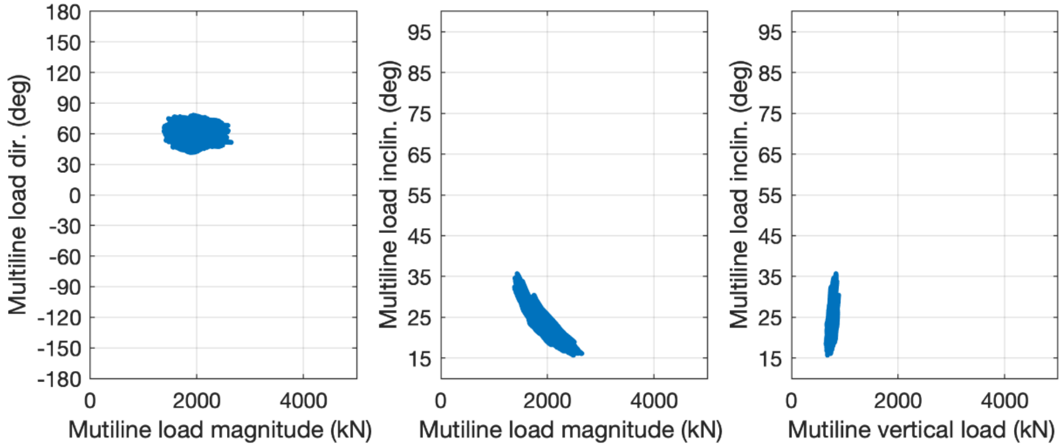
(a) DLC 1.6, unfactored (0°)



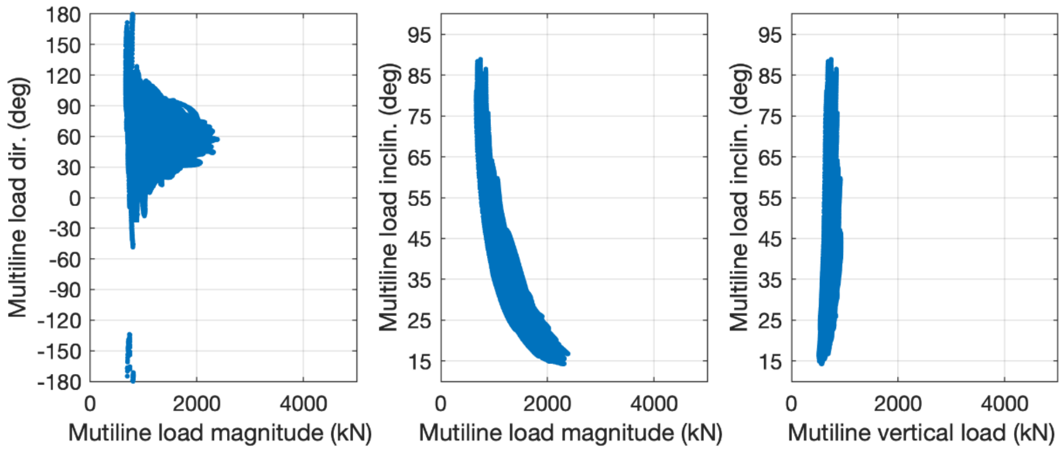
(b) DLC 6.1 unfactored (0°)



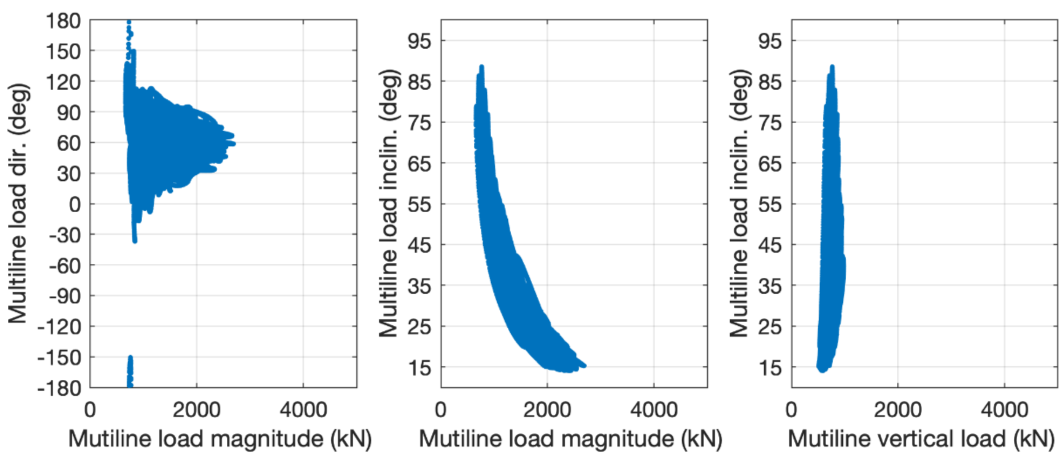
(c) SLC (0°)



(e) DLC 1.6, unfactored (60°)



(f) DLC 6.1 unfactored (60°)



(g) SLC (60°)

Figure 5. Relationship between multiline anchor load magnitude and vertical component and load direction and inclination for NANTUCKET. Loads shown are unfactored.

1.2.5.4 Case 4: VABEACH

At the VABEACH site the turbine spacing is 1,852 m (1 NM) and the simulation water depth is 100 m, resulting in a taut angle of 4.7°.

Table 7. Load characteristics for VABEACH.

a) Load characteristics for VABEACH, DLC 1.6. Unfactored loads, multiply by 1.35 for factored loads.

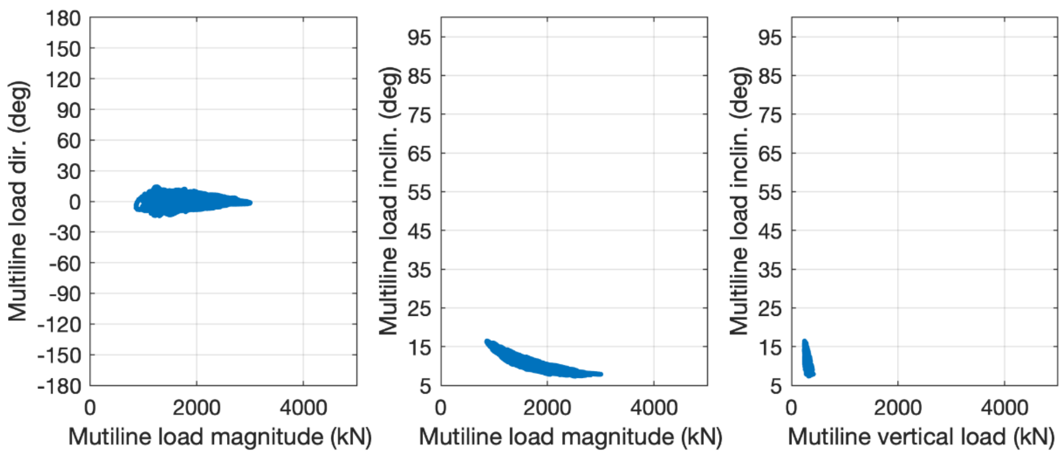
Value	0 degree WWC Maximum (kN)	0 degree WWC Average (kN, deg)	0 degree WWC Stdev. (kN, deg)	60 degree WWC Maximum (kN)	60 degree WWC Average (kN, deg)	60 degree WWC Stdev. (kN, deg)
Single line load	3400	2500	240	2700	2200	100
Multiline						
Magnitude	2700	1800	250	2200	1800	100
Horizontal	2700	1800	250	2100	1800	100
Vertical	390	310	20	440	390	10
Direction	N/A	0	5	N/A	60	5
Inclination	N/A	10	1	N/A	10	1

b) Load characteristics for VABEACH, DLC 6.1. Unfactored loads, multiply by 1.35 for factored loads.

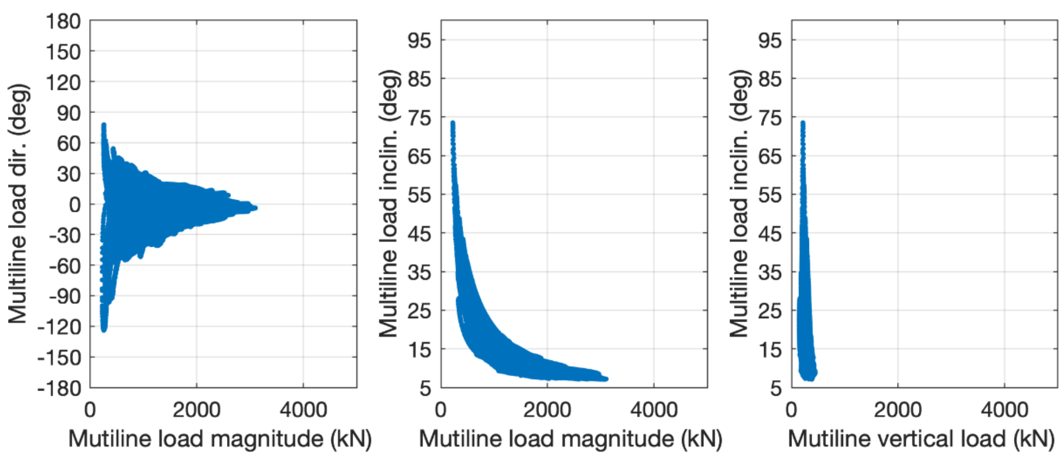
Value	0 degree WWC Maximum (kN)	0 degree WWC Average (kN, deg)	0 degree WWC Stdev. (kN, deg)	60 degree WWC Maximum (kN)	60 degree WWC Average (kN, deg)	60 degree WWC Stdev. (kN, deg)
Single line load	3600	2100	400	2900	1900	250
Multiline						
Magnitude	2900	1400	400	2200	1400	240
Horizontal	2900	1300	400	2200	1300	240
Vertical	420	280	35	440	330	30
Direction	N/A	0	10	N/A	60	10
Inclination	N/A	10	5	N/A	15	5

c) Load characteristics for VABEACH, SLC. Note that for SLC the partial safety factor is 1.0 and therefore factored and unfactored loads are identical

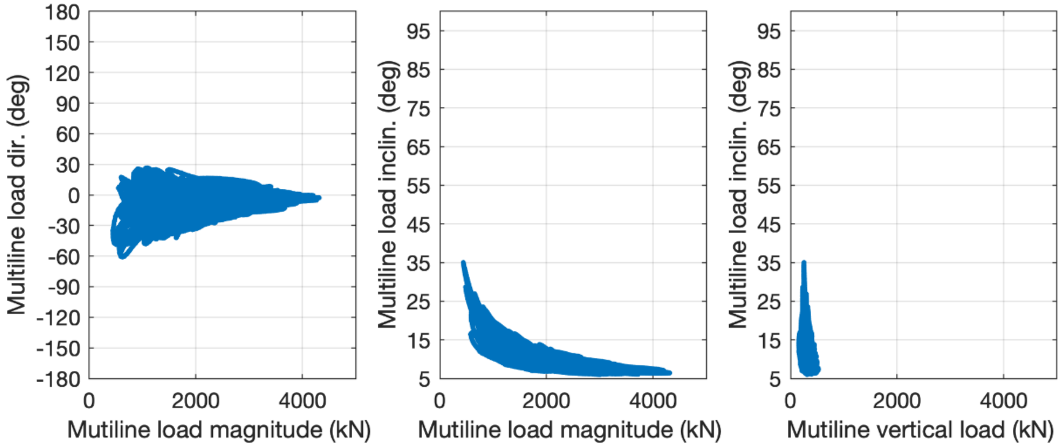
Value	**0 degree WWC** Maximum (kN)	Average (kN, deg)	Stdev. (kN, deg)	**60 degree WWC** Maximum (kN)	Average (kN, deg)	Stdev. (kN, deg)
Single line load	4800	2800	520	3900	2600	340
Multiline						
Magnitude	4100	2100	530	3200	2100	290
Horizontal	4100	2100	530	3100	2100	290
Vertical	500	340	50	580	430	40
Direction	N/A	0	10	N/A	60	10
Inclination	N/A	10	2	N/A	10	1



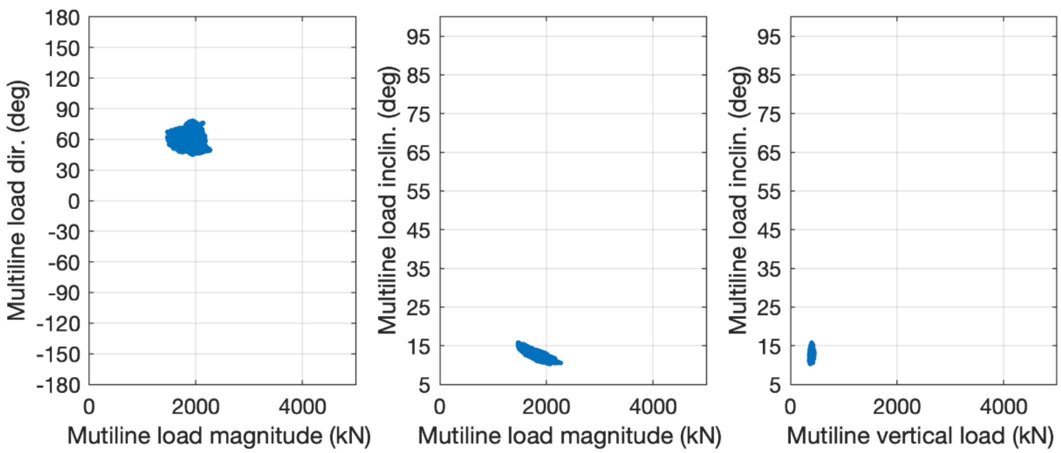
(a) DLC 1.6, unfactored (0°)



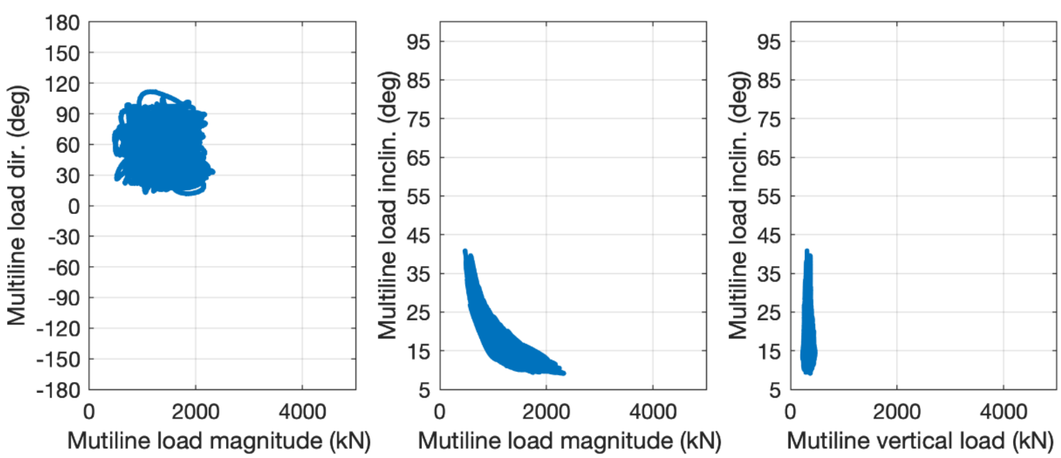
(b) DLC 6.1 unfactored (0°)



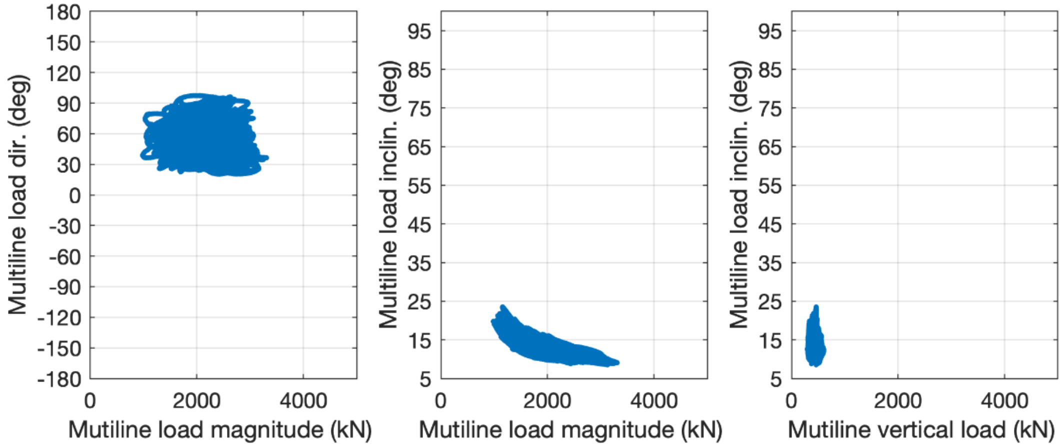
(c) SLC (0°)



(e) DLC 1.6, unfactored (60°)



(f) DLC 6.1 unfactored (60°)



(g) SLC (60º)

Figure 6. Relationship between multiline anchor load magnitude and vertical component and load direction and inclination for VABEACH. Loads shown are unfactored.

1.2.5.5 Case 5: SANTAMARIA

At the SANTAMARIA site the turbine spacing is 1,852 m (1 NM) and the simulation water depth is 450 m, resulting in a taut angle of 24°.

Table 8. Load characteristics for SANTAMARIA.

a) Load characteristics for SANTMARIA, DLC 1.6. Unfactored loads, multiply by 1.35 for factored loads.

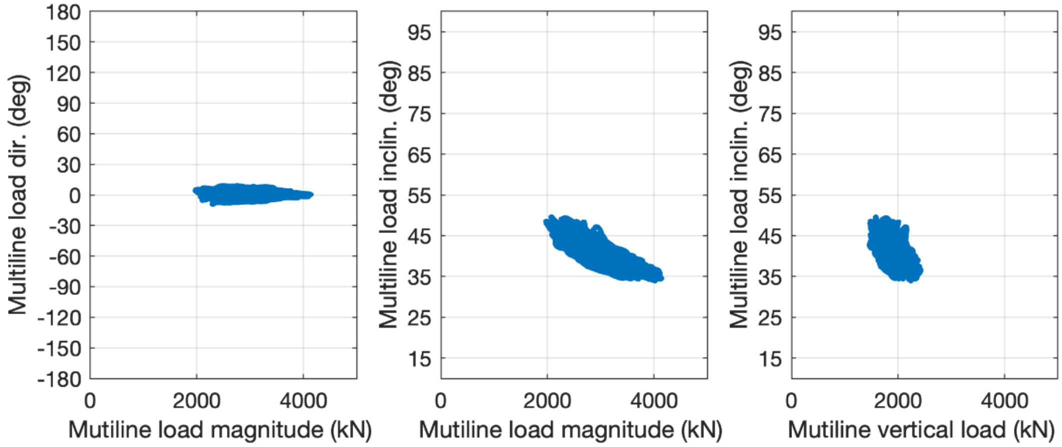
Value	0 degree WWC **Maximum (kN)**	**Average (kN, deg)**	**Stdev. (kN, deg)**	60 degree WWC **Maximum (kN)**	**Average (kN, deg)**	**Stdev. (kN, deg)**
Single line load	4300	3200	290	3300	2900	120
Multiline						
Magnitude	4000	2900	270	3800	3400	110
Horizontal	3200	2200	270	2600	2200	120
Vertical	2400	1900	120	2900	2500	60
Direction	N/A	0	2	N/A	60	5
Inclination	N/A	40	2	N/A	50	2

b) Load characteristics for SANTAMARIA, DLC 6.1. Unfactored loads, multiply by 1.35 for factored loads.

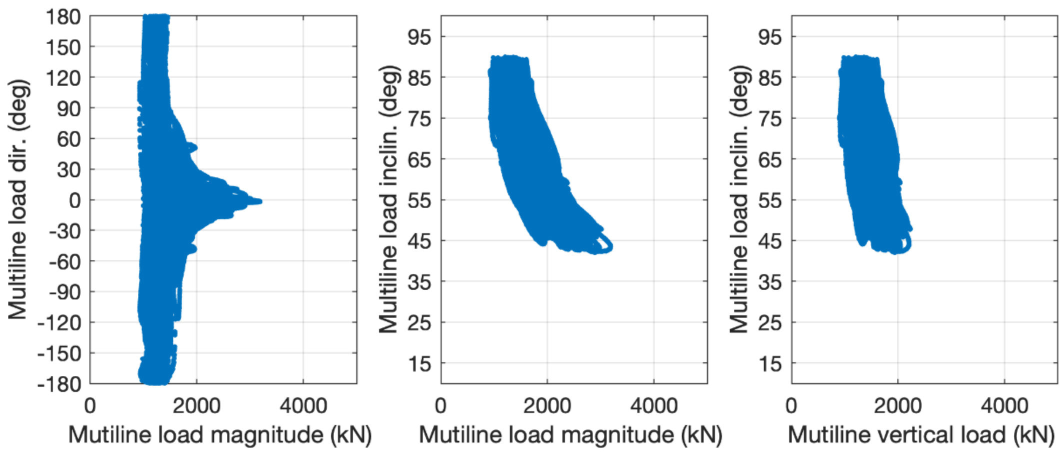
	0 degree WWC			60 degree WWC		
Value	**Maximum (kN)**	**Average (kN, deg)**	**Stdev. (kN, deg)**	**Maximum (kN)**	**Average (kN, deg)**	**Stdev. (kN, deg)**
Single line load	3200	1700	360	2200	1500	170
Multiline						
Magnitude	2900	1600	270	2200	1700	130
Horizontal	2100	700	320	1500	720	230
Vertical	2100	1500	170	2000	1500	130
Direction	N/A	0	25	N/A	60	20
Inclination	N/A	65	10	N/A	65	10

c) Load characteristics for SANTAMARIA, SLC. Note that for SLC the partial safety factor is 1.0 and therefore factored and unfactored loads are identical

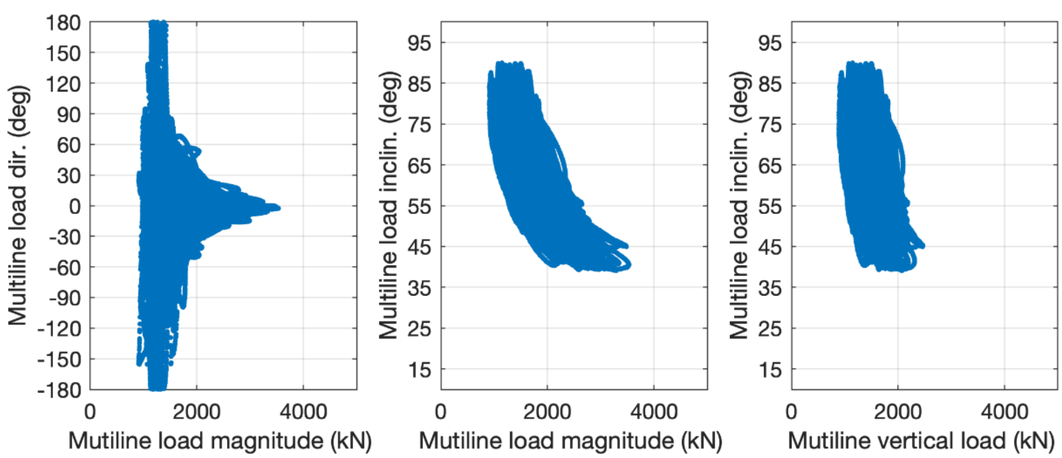
	0 degree WWC			60 degree WWC		
Value	**Maximum (kN)**	**Average (kN, deg)**	**Stdev. (kN, deg)**	**Maximum (kN)**	**Average (kN, deg)**	**Stdev. (kN, deg)**
Single line load	3600	1900	400	2500	1700	200
Multiline						
Magnitude	3300	1800	320	2500	1900	160
Horizontal	2500	890	370	1700	920	250
Vertical	2300	1500	190	2200	1600	150
Direction	N/A	0	20	N/A	60	15
Inclination	N/A	60	10	N/A	60	10



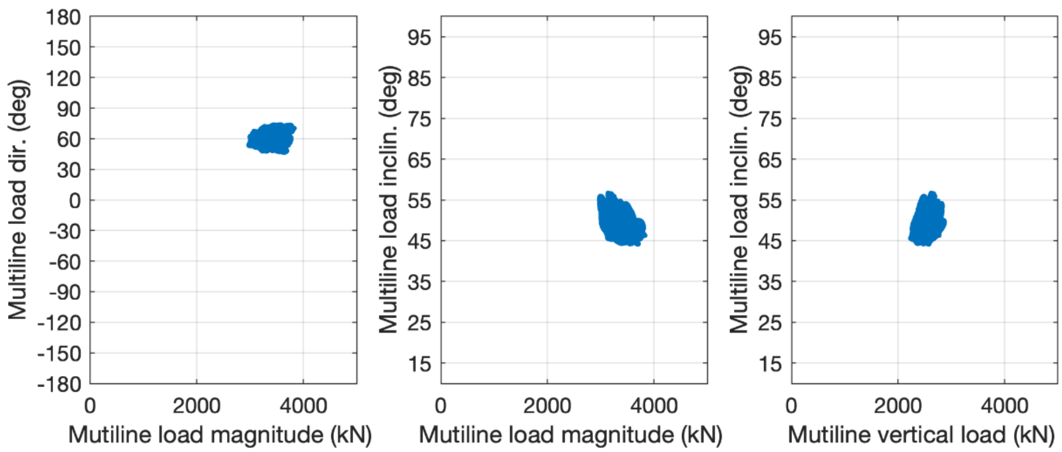
(a) DLC 1.6, unfactored (0°)



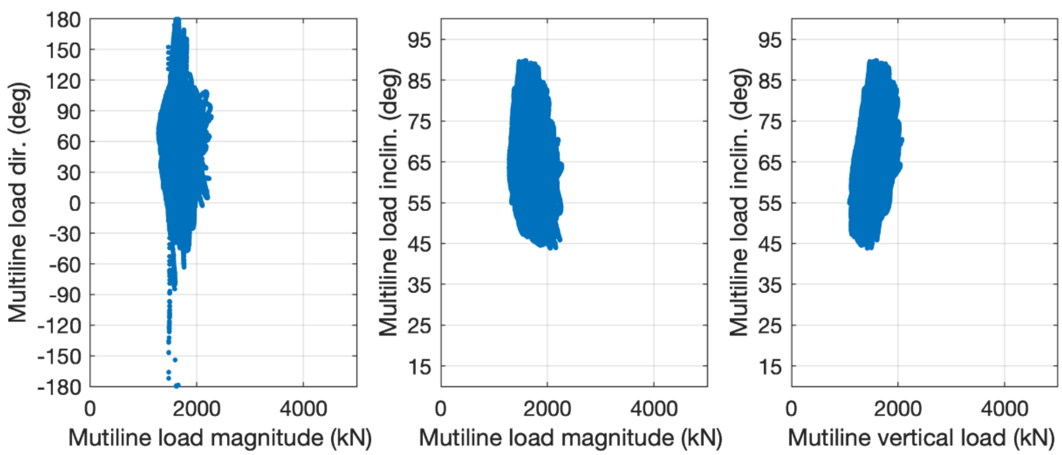
(b) DLC 6.1 unfactored (0°)



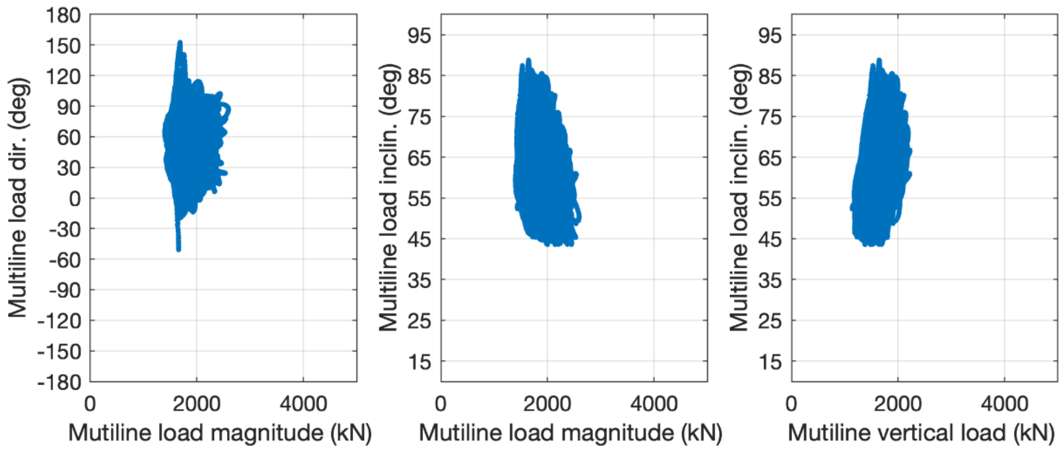
€ SLC (0°)



(e) DLC 1.6, unfactored (60°)



(f) DLC 6.1 unfactored (60°)



(g) SLC (60°)

Figure 7. Relationship between multiline anchor load magnitude and vertical component and load direction and inclination for SANTAMARIA. Loads shown are unfactored.

1.2.6 Summary of Loading Results

The five case studies presented above cover a range of water depths and a variety of load cases, including sets of environmental conditions that represent wind-dominated and wave-dominated loading.

Looking solely at load magnitudes, any of the three load cases can generate the controlling load, either in terms of unfactored or factored loads (in the results tables, the red highlighted loads are the factored maxima and the orange highlighted loads are the absolute maxima)

The variability of multiline load direction and inclination is much smaller for DLC 1.6 than for the two non-operational cases (as seen in the figures). This likely results from the relative importance of the mean thrusts acting on each turbine during generation operation such that the wind load is expected to be larger during operation than during extreme conditions, despite the higher wind speeds associated with the non-operational load cases. Variability of the loads themselves are also generally smaller (except for SANTAMARIA) for DLC 1.6 for the same reason.

Horizontal components of the load are larger at all sites except SANTAMARIA, the deep water site with the steepest taut mooring line angle. Additionally, variability of the vertical component of the load is substantially smaller than variability of the horizontal component of the load, an effect attributable to the relatively low attachment angles of the taut mooring lines.

Only in the extreme load cases for SANTAMARIA are the vertical components of the multiline anchor comparable to the horizontal components. For all other cases the horizontal components are larger, often substantially so. It would appear, then, that for turbine spacing of 1 NM, there is a transition depth between 200 m and 450 m for which the vertical component of the load becomes larger than the horizontal component. Even at the 450 m water depth of SANTAMARIA, however, the variability of the vertical component remains smaller than that of the horizontal component. There may exist a deeper transition at which vertical variability and cycling becomes dominant.

Due to the additive nature of the vertical components of the taut mooring line tensions, in contrast to the horizontal component load cancellation effect caused by the opposing mooring lines, the resultant angle of load inclination is substantially steeper than the taut mooring line angles themselves. When there is a load case generating the highest inclination resultant, it is DLC 6.1 with the shallowest resultant in DLC 1.6. The smallest differences between the taut line angle and the resultant inclination occur for the shallow water VABEACH site, while the largest difference occurs for the deep water SANTAMARIA site. Maximum load inclinations are substantially steeper than the mean inclinations, reaching nearly vertical for MONHEGAN, NANTUCKET, STONEWALL and SANTAMARIA, and nearly 75° at VABEACH. These large inclinations occur for low load magnitudes (except at the deeper water SANTAMARIA site), but the magnitude of the vertical component of the load is relatively constant across load inclination angles. STONEWALL has relatively shallow water (150 m) but steep load inclinations. This may be due to the wave dominance of the environmental conditions at STONEWALL as wave loads on the platforms are nearly mean-zero, leading to larger vertical components in wave-dominated sites.

Loads for a WWC of 60^{o} generate lower magnitude loads than for 0^{o}, likely because, for 60^{-} WWC there are two heavily loaded lines (1,2) mooring turbines that are down-WWC of the anchor and, since those lines are independently loads by their respective platforms, they are not likely to reach peak demand simultaneously.

1.2.7 Anchor Design

Using the loading results from the tables above some possible configurations of the Triton Anchor were designed. This was done to gain a general idea of the scale of the system that would be necessary to deploy Triton Anchor at sites similar to the ones analyzed in this study. The results for skirt geometry and anchor arrangement are shown below in Table 9. Loose sand was assumed for this study and is not necessarily representative of soil conditions at these sites; site investigation would have to be performed at each location to design accurate anchor configurations.

Table 9. Triton Anchor Configurations

Location	System	Skirt Len.	Skirt Dia.	Shaft Size	Helix	Anchors	Maximum Embedment Depth	Price total	Weight
(-)	(-)	(ft)	(ft)	(in)	(-)	(Qty)	(ft)	($)	(mT)
Monhegan Island	Single	21	28	6.625	2x16’’	7	28	$160,391.44	36
	Multi	18	25	6.626	1x24’’	10	21	$125,388.07	28
Stonewall	Single	23	23	4	2x16’’	7	25	$141,507.74	32
	Multi	13	25	5	1x24’’	8	15	$88,114.60	20
Nantucket	Single	10	27	2.875	1x16’’	6	14	$71,263.44	16
	Multi	10	23	2.875	1x24’’	8	14	$61,465.35	14
VA Beach	Single	10	27	6.625	1x16’’	6	14	$71,263.44	16
	Multi	10	23	6.625	1x16’’	9	14	$61,739.31	14
Santa Maria	Single	10	23	2.875	2x16’’	10	18	$62,796.03	14
	Multi	10	23	2.875	2x16’’	14	18	$64,204.98	15

Note that in Table , above, the helix column is expressed as m x n, in which m = number of helical plates on the shaft and n = the diameter of the helical plate in inches. The savings when going from single line to multi line configurations for an offshore wind farm are shown in Table 10, below.

Case	Price total	Savings going from Single to Multi line (%)
Monhegan Single	$160,391.44	22
Monhegan Multi	$125,388.07	
Stonewall Single	$144,149.45	38
Stonewall Multi	$89,142.99	
Nantucket Single	$71,263.44	14
Nantucket Multi	$61,465.35	
VA Beach Single	$71,263.44	13
VA Beach Multi	$61,739.31	
Santa Maria Single	$62,796.03	-2
Santa Maria Multi	$64,204.98	

Table 10. Price comparisons for Triton Anchor configurations: Single Line Vs. Multiline

The savings shown in the table above does not account for the decrease in total anchors per field, only the decrease in cost per anchor.

1.2.8 Anchor Loading Conclusion

The purpose of this study was to expand the knowledge of the loading conditions that Triton Anchor may see when deployed in a variety of environments. This study was necessary due to the unavailability of commercial platform design loads and difficulty in finding them via physical testing. Using the information presented, realistic loading conditions were quantified and further research interests could be determined. This study provided Triton with horizontal and vertical loads to use in developing the design process of Triton Anchor. Differences in mooring line angles, water depth, wind speed, wave height, and ocean current characteristics give Triton a larger scope of the different needs that Triton Anchor will be able to accommodate.

The study produced valuable information regarding the effect of inclination angle and load direction of multiline anchors on vertical/horizontal load variability. The results have shown that the vertical load varies very little with changes in multiline load inclination; this means that the horizontal load is the primary factor in the changes in inclination angle of the resultant load. Cyclic loading is a future research interest for Triton Anchor and this study is indicating that an emphasis on cyclic loading of the skirt (horizontal load carrying) rather than the helical anchors (vertical load carrying) should be considered.

This study focused on multiline anchor configurations so that a comparison could be made between multiline and single line anchor loading conditions. With 3 turbines moored to one anchor (at an angle), the loads were not 3x more than the single line loads, as could be expected. The multiline anchor configurations allow anchors to have lower maximum loading cases and fewer anchors per field. In addition, multiline anchor configurations usually cost less than single line configurations while servicing more turbines. The exception to this occurred at the Santa Maria site (Case 5), which saw the deepest water and highest mooring line angle. This suggests that multiline may not be the cheapest option for deep water sites, but more deep water sites would need to be considered to confirm this.

A variety of load cases were implemented to investigate which of them (DLC 1.6, DLC 6.1, or SLC) would normally control anchor design. In the cases presented above, different load cases governed design for each case. This suggests that the design load that governs anchor design changes between sites and all cases should be checked in each site and condition. Site specific loading is required for all anchor loading analysis and cannot be estimated or compared from other sites even with the same platform/mooring configuration.

Multi-line anchoring should be considered for floating offshore wind farms as the loading cases reduce the horizontal capacity required which has a large impact on anchor size which ultimately reduces anchor costs.

Finally, the presented FAST analysis was done to provide loading information to ABS to determine test load conditions that would be representative of deployment. The ABS test will be a pull test to failure and should be scalable; the results from this analysis will help to ensure that.

This report shows that anchors are designed to site and project specific conditions and equipment. Knowing a range of anchor loads possibilities is helpful but ultimately do not dictate anchor certification. Based off this data, ABS will be certifying the anchor design process and not site-specific conditions. The process will be applied in a commercial setting to determine site specific anchor designs.

1.3 Cyclic Loading

This section describes the cyclic loading of multiline anchors due to floating offshore wind turbines (FOWTs). Each anchor has 3 lines attached to it from different FOWTs. Loads were generated by simulations in OpenFAST for the Santa Maria site using the environmental conditions detailed in the accompanying environmental report. Results were evaluated for wind wave current (WWC) directions of 0 and 60 degrees for loads corresponding to DLC 1.6, DLC 6.1, and SLC.

1.3.1 Methodology

This section covers the signal processing and provides a brief overview of the Santa Maria site.

1.3.1.1 Signal Processing

The raw load time histories output from OpenFAST exhibited a significant amount of high-frequency noise. To reduce this noise, load time histories were passed through a lowpass filter 4 times and peaks and troughs in the filtered signal were then identified, with only peaks and troughs greater than 1 second apart being retained. These peaks and troughs were connected with linear segments to create a modified signal that retained the cycle amplitudes and periods of the physically meaningful, noise-free, signal. Rainflow counting was then applied to the modified signal to characterize the cyclic amplitudes and periods present in the multiline load time history. Figure 8 (a) compares the original signal to the signal processed through the lowpass filter and (b) the modified, piecewise linear signal.

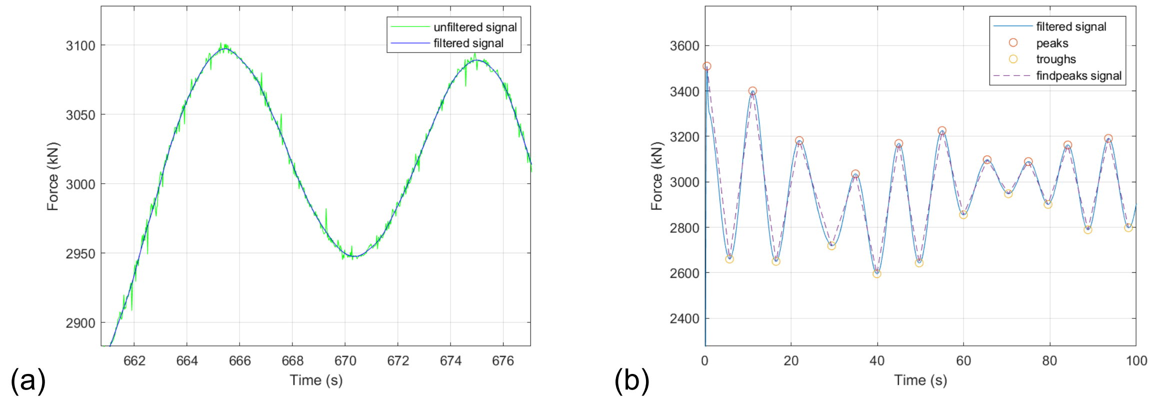


Figure 8. (a) Original signal with high-frequency noise vs filtered signal using lowpass filter and (b) modified piecewise linear signal.

1.3.1.2 Santa Maria Site Overview

The Santa Maria site, off the coast of California, has a simulation water depth of 450 m. The environmental conditions in Table 11, taken from the accompanying environmental report, were used for the corresponding load cases.

Table 11: Environmental conditions

Load case	Wind speed (m/s)	Wave height (m)	Wave period (s)	Current (m/s)
DLC 1.6	10.6	7.6	10.3	0.07
DLC 6.1	32.5	9.2	11.3	0.24
SLC / I.1	37.1	9.8	11.7	0.28

1.3.2 Results

For each load case, six 1-hour multiline simulations were run in OpenFAST. These simulations are concatenated and analyzed as a single 6-hour dataset as permitted by standard practice.

1.3.2.1 0 deg – DLC 1.6

Figure 9 shows a section of a time history of multiline loading, processed using the methodology detailed above. The load case is DLC 1.6. The cycle periods are primarily driven by the wave periods of this wave train, which peak in energy at 10.3 s.

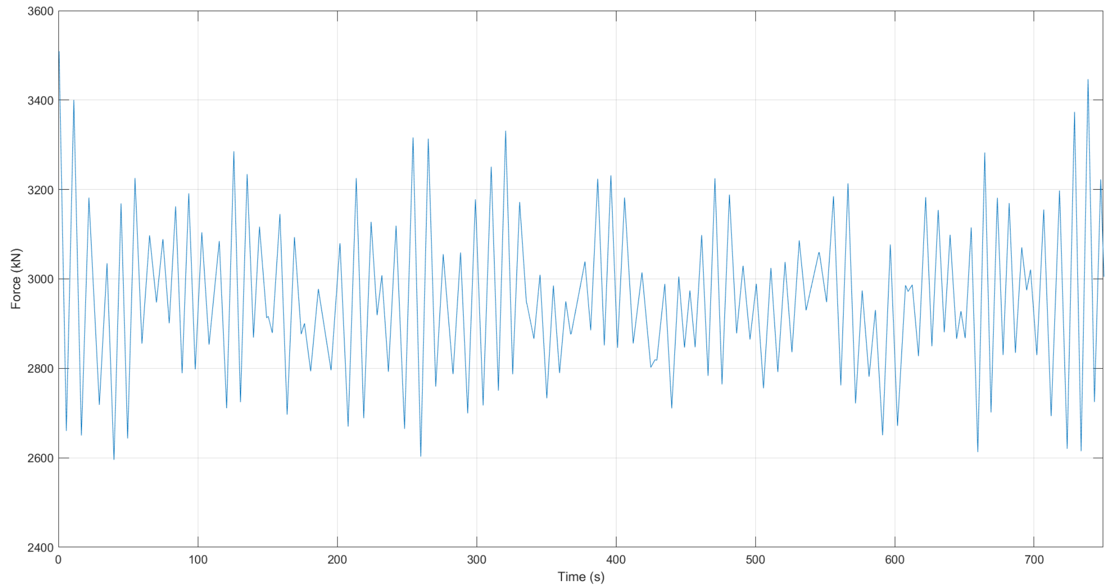


Figure 9: Sample 750 s time history of multiline loading

Figure 10 presents the 6-hour cycle amplitude histogram for DLC 1.6. The most common cycle amplitudes are between 150 and 200 kN with the number of occurrences decaying rapidly above 200 kN. The maximum recorded cycle amplitude is 659 kN.

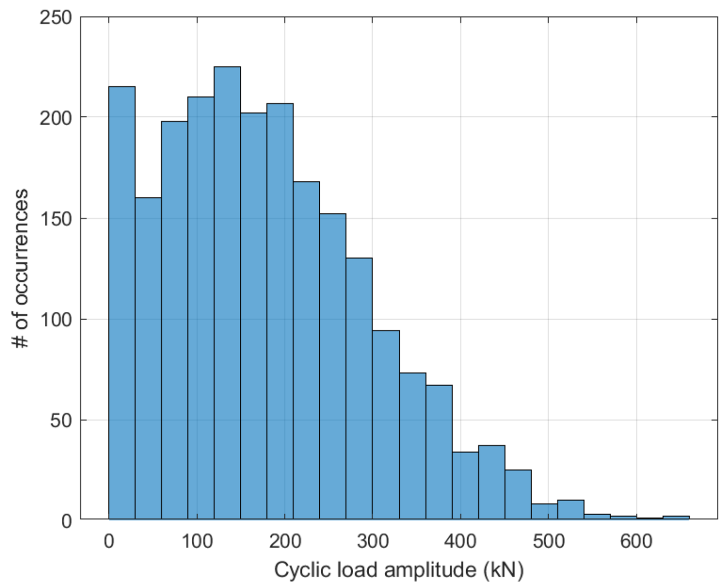


Figure 10: 6-hour cycle amplitude histogram for DLC 1.6 for multiline time history, 0 deg

Figure 11 displays the cycle periods shorter than 200 s (the primary natural frequencies of the platform are approximately 100 s). The median cycle period for these 6 hours is 10.55 seconds (Table), which is approximately the peak period for the wave train. Most of the periods are close to this value, while a few larger period outliers can be seen.

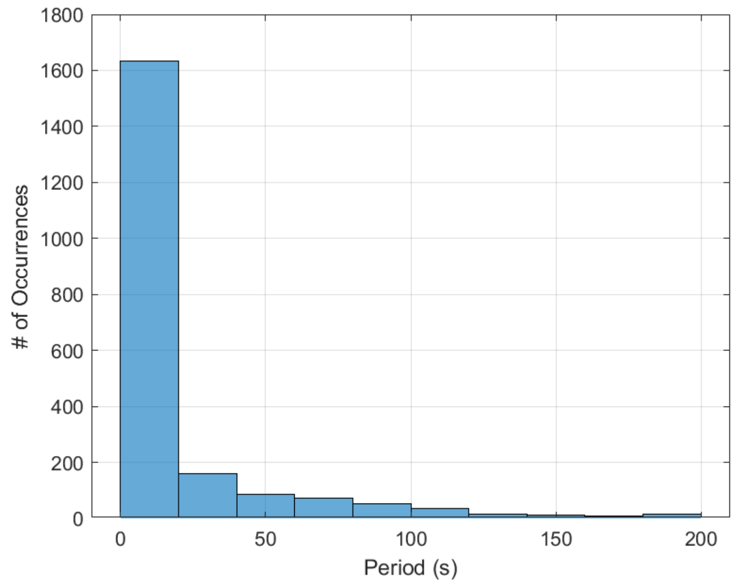


Figure 11: 6-hour cycle period histogram for DLC 1.6 for multiline time history, 0 deg

Figure 12 displays the relationship between cycle amplitudes and their corresponding periods. As the majority of the periods are around 10 s, the markers are concentrated around the x axis. A few outlier periods and loads can be seen.

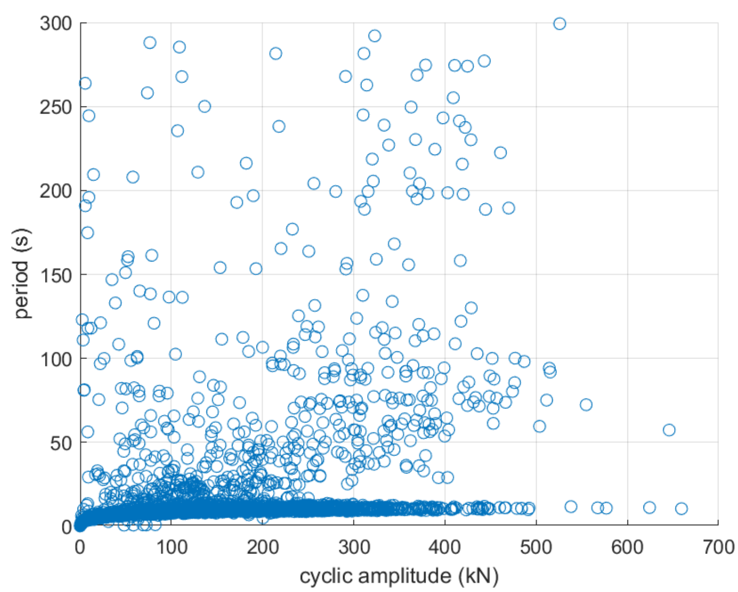


Figure 12: Cyclic amplitude vs period scatter plot for multiline time history

1.3.2.2 0 deg Cycle Comparisons

Figure 13 compares the mean cyclic load amplitude for a few different loading metrics. Anchor Tension 2 is the single-line loading with the largest mean load, so it is included to compare single-line loading to multiline loading. Multi refers to the magnitude of the multiline force, while multi-horiz is the horizontal component of the multiline force, and multi-vert is the vertical component of the multiline force. For all load cases, the multiline amplitudes were smaller compared to their single-line counterpart. Amplitudes increased from DLC 1.6 to 6.1 to SLC, since the cycles are driven by the waves, and the wave peak periods and significant wave heights increase with load case. This data is also presented in Table 13, along with the corresponding maximum values and standard deviations. For context, the mean values for the different load time histories are provided in Table 12. In Figure 13, for DLC 6.1 and SLC, the mean multiline horizontal cyclic amplitudes are greater than the multiline cyclic amplitudes, which may seem counterintuitive, but it is important to remember that the mean multiline load is still greater than the mean multiline horizontal load (Table 12).

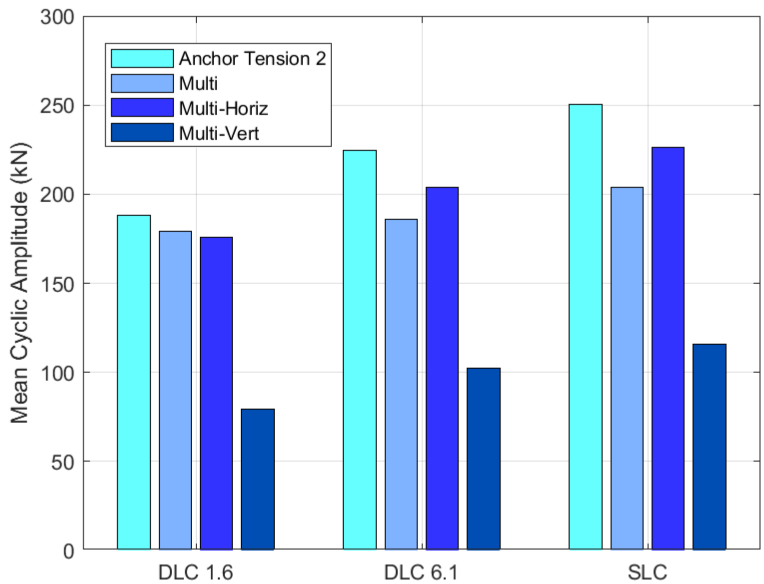


Figure 13: Mean cyclic amplitudes, 0 deg

Table 12: Mean Values for Load Time Histories, 0 deg

	DLC 1.6	DLC 6.1	SLC
Anchor Tension 2 (kN)	3183	1846	2017
Multiline (kN)	2928	1803	1918
multiline-horizontal (kN)	2218	698	902
multiline-vertical (kN)	1911	1650	1678

Table 13: Cycle amplitudes, 0 deg

		DLC 1.6	DLC 6.1	SLC
Anchor Tension 2	*mean (kN)*	188	224	251
	max (kN)	684	952	1071
	std	124	153	172
multiline	*mean (kN)*	179	186	204
	max (kN)	659	723	888
	std	119	125	140
multiline-horizontal	*mean (kN)*	176	204	226
	max (kN)	633	772	932
	std	117	145	164
multiline-vertical	*mean (kN)*	79	102	116
	max (kN)	297	444	542
	std	56	77	89

Table 14 displays the cycle periods. Cycle periods between different load time histories did not vary significantly. For analyzing the periods, median values were taken instead of mean values; the outlying large values of some cycle periods cause the mean value to provide a misleading metric. Median cycle periods aligned closely with their corresponding wave peak period.

Table 14: Cycle periods, 0 deg

		DLC 1.6	DLC 6.1	SLC
Anchor Tension 2	*median (s)*	10.550	11.850	12.250
	max (s)	3605	2045	2566
	std	347	166	234
multiline	*median (s)*	10.550	11.700	12.050
	max (s)	4598	1640	2987
	std	461	156	251
multiline-horizontal	*median (s)*	10.750	11.350	11.700
	max (s)	2449	4160	2904
	std	232	321	307
multiline-vertical	*median (s)*	10.800	11.450	11.800
	max (s)	4118	2088	2360
	std	401	187	195

1.3.2.3 60 deg Cycle Comparisons

Figure compares the mean cyclic load amplitude for a WWC direction of 60 degrees. Like the 0 deg run, Anchor Tension 2 is again utilized as a representative single-line metric; in WWC of 60 degrees, lines 2 and 3 split the majority of the loading relatively evenly. The load amplitudes are significantly less than their 0 deg counterparts. For context, the mean values for the different load time histories are provided in Table *15*.

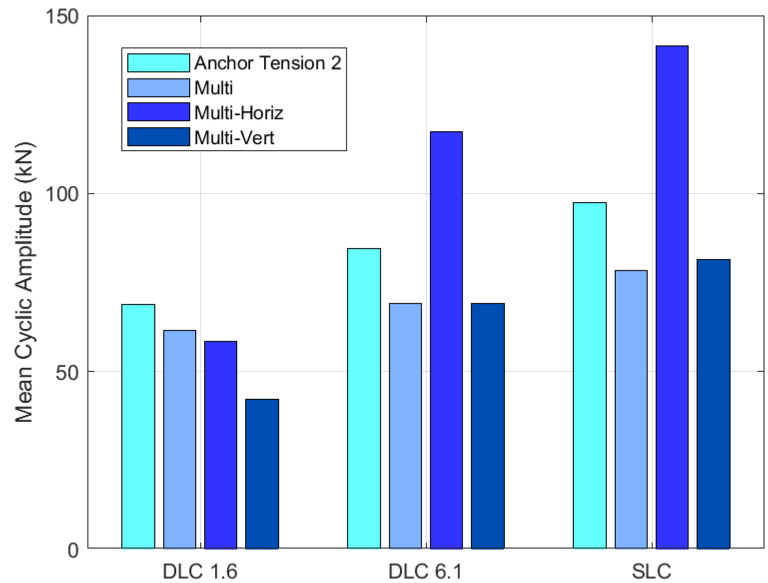


Figure 14: Mean cyclic amplitudes, 60 deg

Table 15: Mean Values for Load Time Histories, 60 deg

	DLC 1.6	DLC 6.1	SLC
Anchor Tension 2 (kN)	2768	1657	1783
Multiline (kN)	3258	1817	1941
multiline-horizontal (kN)	2199	689	883
multiline-vertical (kN)	2404	1670	1717

Table 16: Cycle amplitudes, 60 deg

		DLC 1.6	DLC 6.1	SLC
Anchor Tension 2	*mean (kN)*	69	85	97
	max (kN)	360	470	569
	std	56	74	87
multiline	*mean (kN)*	62	69	78
	max (kN)	304	390	421
	std	50	60	69
multiline-horizontal	*mean (kN)*	58	117	142
	max (kN)	321	678	741
	std	49	116	129
multiline-vertical	*mean (kN)*	42	69	82
	max (kN)	224	400	430
	std	36	63	72

Table 17 displays data regarding the cycle periods for 60 deg. While the median values did not significantly vary from their corresponding 0 deg counterparts, the maximum values and standard deviations are smaller.

Table 17: Cycle periods, 60 deg

		DLC 1.6	DLC 6.1	SLC
Anchor Tension 2	*median (s)*	11.000	11.150	11.325
	max (s)	675	1108	1251
	std	97	110	129
multiline	*median (s)*	10.500	10.700	11.225
	max (s)	2111	1200	2072
	std	188	117	182
multiline-horizontal	*median (s)*	10.125	11.050	11.300
	max (s)	3183	908	2612
	std	239	136	222
multiline-vertical	*median (s)*	10.350	11.200	11.350
	max (s)	1454	2171	2325
	std	127	197	236

1.3.3 Results

This section characterized the cyclic loading on a 3-line shared anchor. Simulations for the three design cases were conducted for the Santa Maria site. Cycles were found to be primarily driven by the waves, and their periods were highly correlated to their corresponding peak wave periods. Cyclic amplitudes also increased with load cases, as the load cases wave heights and peak periods increased. 0 deg WWC had larger amplitudes than 60 deg.

2 American Bureau of Shipping New Technology Qualification Process

Triton Systems, Triton, is walking through the American Bureau of Shipping (ABS) New Technology Qualification (NTQ) Process, illustrated below in Figure 9.

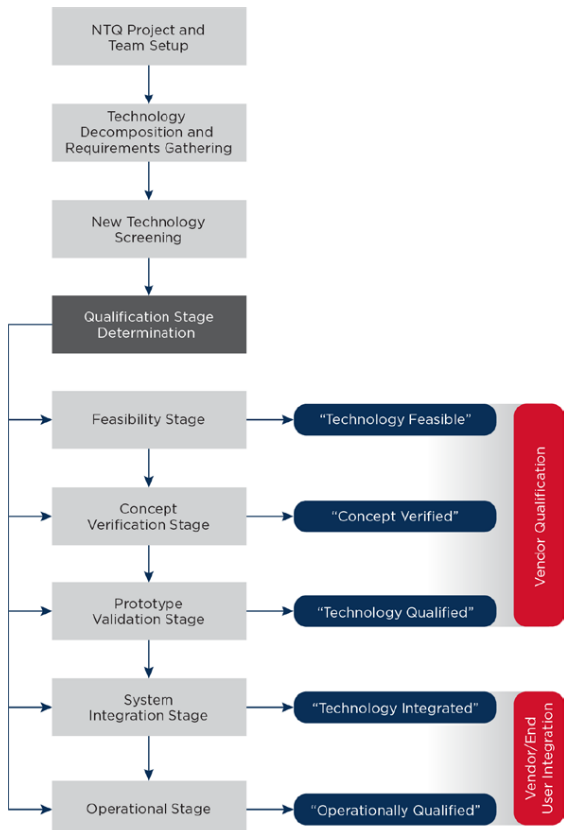


Figure 15: ABS NTQ Process Diagram

Triton has been providing information to ABS in various formats to complete the sequential stages of the process, listed below.

1. Feasibility Stage
2. Concept Verification Stage
3. Prototype Validation Stage
4. System Integration Stage
5. Operational Stage

As of the completion of this report, Triton has completed stages 1 through 4 and intends to finish the Operational Stage soon with an open water system demonstration.

The following subsections detail each of the stages completed during this program.

2.2 Feasibility Stage

For the Feasibility Stage, Triton completed the high-level technology and methods documents. Properly defining a new technology is a critical aspect of NTQ. These included but are not limited to the following documents:

- System Requirements Definition Document (SRDD)
- Systematic Screening Report
- Design basis document
- Risk Assessment
- Technology Feasibility Report

These documents defined and set the baseline requirements for the new technology and were derived from functional and technical specifications. The requirements are continuously defined for each level within the system hierarchy as applicable. As the design matures through development and more knowledge is gained through qualification, these requirements may be subject to change.

The Feasibility Stage Statement of Maturity is included in the appendix.

2.3 Concept Verification Stage

The next stage of the NTQ process is to perform detailed engineering studies and physical or virtual model testing. This included some of the following additional testing reports and documentation to summarize each activity.

- Group effects of helical anchors
- Horizontal capacity analysis report
- Skirt installation analysis
- Preliminary manufacturing plan
- Template design analysis report

Each activity further defined the concepts derived at the origin of this program. We broke the anchor system apart into subsystems, helical piles, skirt, and template to analyze their behaviors as individual components. Although each component has been proven individually in various fields of application, our objective was to calibrate our numerical modeling and analyses to match prior and current testing data.

The preliminary manufacturing plan identified current supply chain bottlenecks and efficiencies unique to the Triton Anchor, such as the use of COTS helical anchors, shown below.

Figure 16. Mass produced helical piles

In addition to these new activities, we continued to update the on-going governing documents listed in the Feasibility Stage.

The Concept Verification Stage Statement of Maturity is included in the appendix.

2.4 Prototype Validation Stage

After receiving the Concept Verification Stage Statement of Maturity (SOM), we entered the Prototype Validation Stage which has the main objective of validating the models derived during the Concept Verification Stage.

During this stage we completed the following activities:

- Buckling and structural design assessment under horizontal loading
- Anchor case study strength assessment and FEA simulation
- Pile connection FEA modeling
- Onshore test plan development
- Onshore test site soil investigation
- Onshore CPT analysis
- Onshore Anchor Design & Fabrication

These activities mostly demonstrated the detailed process the team utilizes to develop an anchor system. In adherence to the Design Basis, we walked through the design process of the anchor based on the site-specific soil properties. This included conducting in-field soil investigation using a cone penetration test (CPT) rig capable of measuring the strength of the soil at its different layers beneath the surface. Using this data, the team constructed a ground model that accurately should the varying layers of soil. Based on this ground model and the planned testing loads, the team designed an anchor and modeled the expected behavioral responses to loading scenarios. This model was then fabricated for in-field testing and model validation.

The Prototype Validation Stage Statement of Maturity is included in the appendix.

2.5 Systems Integration Stage

The Systems Integration Stage took the anchor test planning from the previous stage to full-scale execution. The following list shows the primary activities accomplished during this stage.

- Risk assessment workshop
- Parametric study of full anchor system
- Full system simulation report
- Clay numerical analysis
- Structural analysis of horizontal loading on skirt
- Land test demonstration
- Test plan preparation for offshore demonstration

The risk assessment workshop was led by ABS and resulted in an updated comprehensive HAZID and risk registrar. This helped us prepare for the upcoming land demonstration test where we could walk through potential risk mitigation measures. A new parametric study was performed to quantify the helical anchor's abilities to resist horizontal movement and rotation of the skirt under horizontal loading.

The following list details the anchor configurations to be analyzed during this study:

- Helical Plate Diameter (D): 45.7cm, 40.6cm, and 35.6cm with vertical spacing of 5D between plates
- Skirt Thickness (t): 12.7mm
- Pile Shaft Diameter: 11.4cm (0.86cm wall thickness)
- Skirt Diameter (d): 3m, 8m, and 13m
- Horizontal Anchor Spacing: 3, 4, and 5D
- Embedment Depth (z): 25, 50, and 75 z/D
- Sand Profiles: 3

The numerical analysis of the anchor system in clay included testing of installation effects, monotonic loading, and cyclic and creep behaviors. The main takeaway from the clay analysis so far is that the spacing between piles can be much closer without compromised interference than in sand. Additional physical testing is underway to be conducted to validate these models. Further structural analysis of the anchor system under load identified hot spots and high stress areas as well as areas that could benefit from reduced component sizing.

With ABS onsite to witness, the successful land test demonstration was completed with two full scale anchors. The following figures show the test configurations and summarized results.

Figure 17: Vertical Test Configuration

Figure 18: Horizontal Test Configuration

The following figures illustrate the test results.

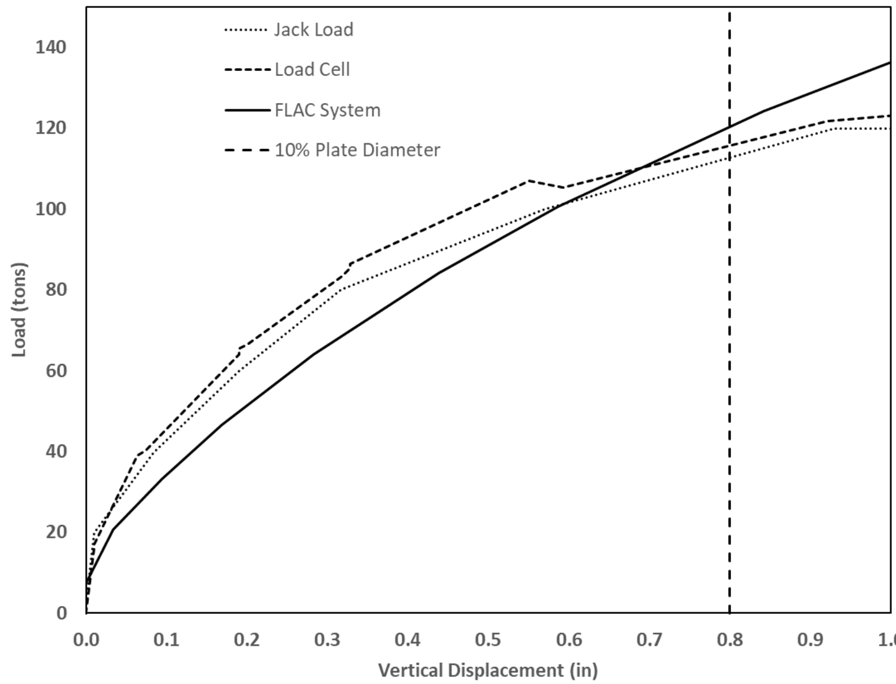


Figure 19: Vertical Load Test

As shown above, one anchor was load tested vertically with capacity validated within 3% of modeling. The Jack Load read 113 tons, the Load Cell read 116 tons, and the design load from FLAC was 120 tons.

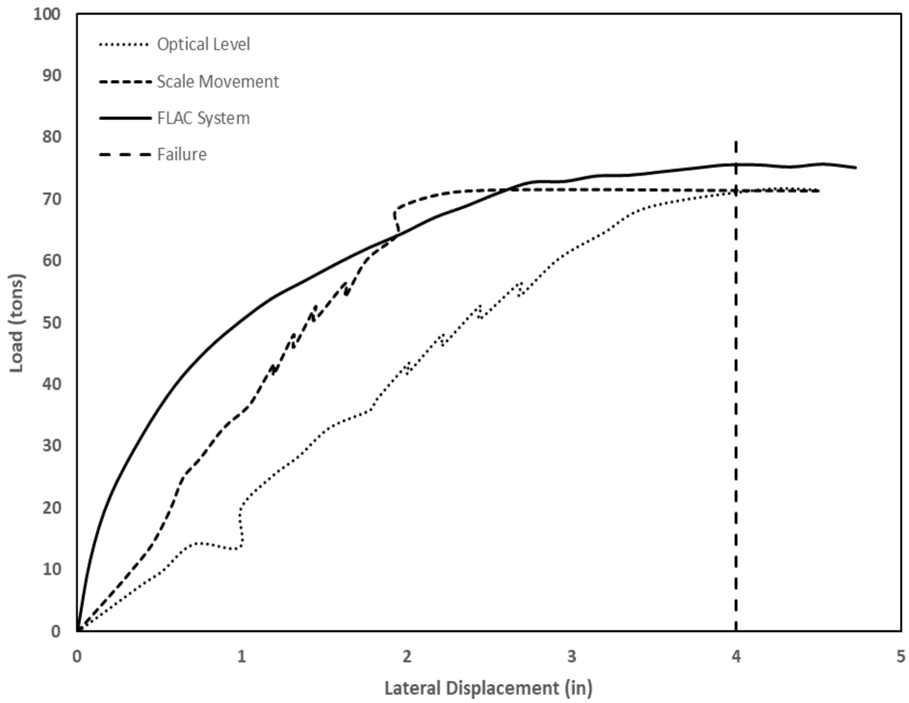


Figure 20: Horizontal Load Test

The second anchor was horizontally load tested and resulted in a capacity correlation within 4% of expected. The Optical Level read 72 tons, the Scale read 72 tons, and the design load from FLAC was 75.5 tons. From a high-level anchor system, the test proved the anchor design code accurate in designing for capacity.

After the land test was completed, offshore demonstration planning was conducted to prepare the anchor installation tool and team for offshore soil investigation, and vessel coordinated efforts to install an anchor and pull to geotechnical failure.

The following figure illustrates the open water activity that was planned during this stage. Execution of the test will be conducted in the next stage.

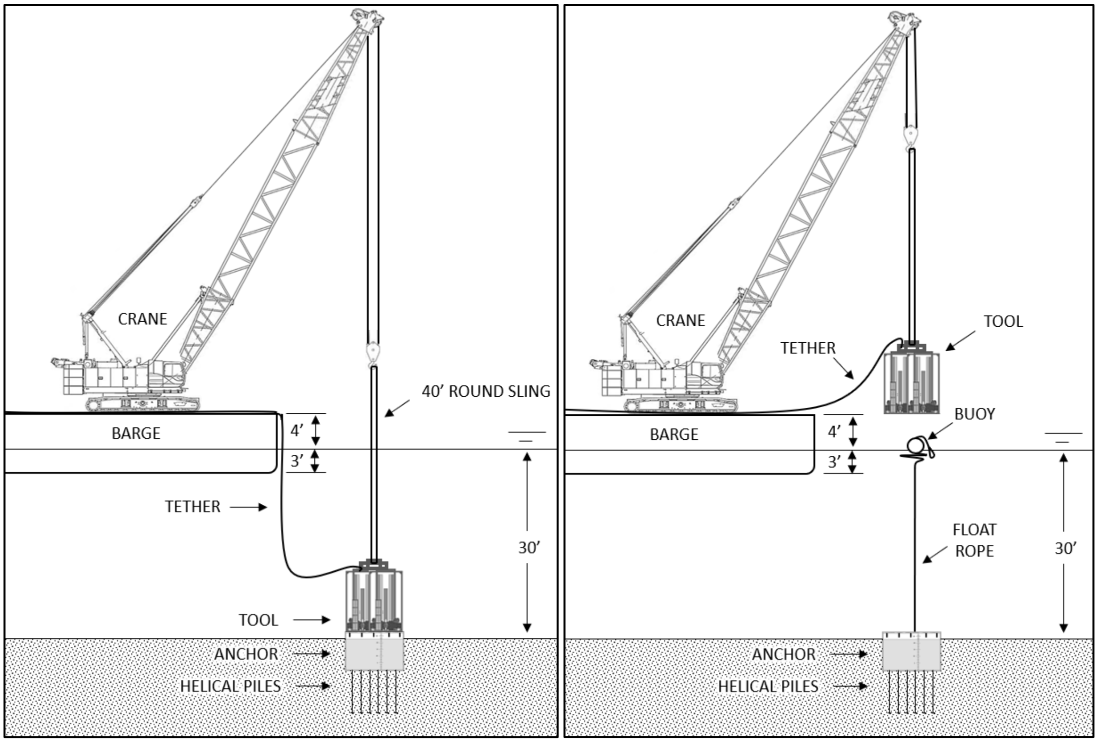


Figure 21: Helical Pile Installation

As shown above, the tool and anchor will be lowered to the seabed off a barge and controlled through a tether to the surface. After installation, the tool will be recovered leaving a recovery line attached to the anchor with a surface buoy. The anchor will sit undisturbed for a week allowing for sufficient geotechnical “set-up” time. Set-up time is the duration required to allow the soil to partially reconsolidate around the anchor after installation.

The following figure illustrates the pull-test configuration.

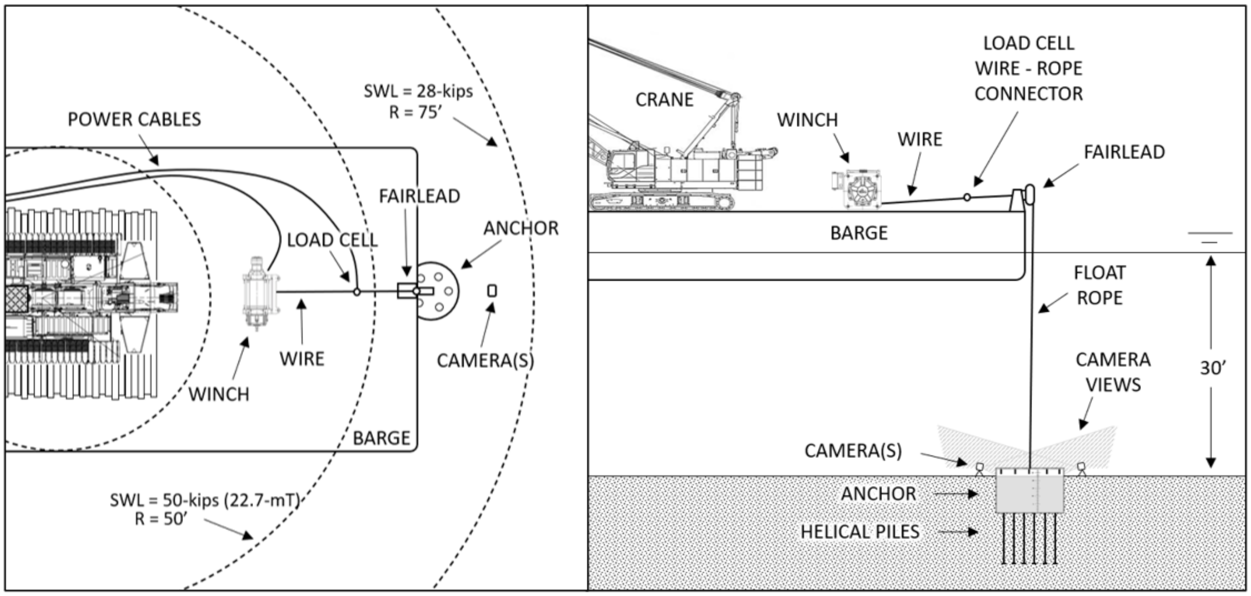


Figure 22: Pull Test Configuration

The figure above illustrates the general plan to pull the anchor to geotechnical failure. A winch will be secured to a barge with an overboarding sheave. The line suspended from the buoy will be tied into the anchor line. Cameras will be set on the seafloor for general observation. Data collection will include installation torque from the tool and total anchor embedment depth. A camera will be deployed subsea to observe the final anchor position and embedment depth.

The anchor pull test will be the first offshore open water Triton Anchor demonstration of capacity. This test will show the anchor is able to withstand design load pull requirements.

Once the anchor is pulled to completion, the anchor will be fully recovered.

The System Integration Stage ABS Letter of Intent to issue the Statement of Maturity is included in the appendix.

2.6 Operational Stage

During this stage, Triton will continue the advancement of the technology through operational demonstrations in an environment representative of the conditions expected during operations. Offshore planning was started during the previous stage and continues through site determination, soil investigation, anchor design and fabrication, and ultimately, anchor installation and pull testing.

During this stage Triton will complete the following activities:

- Production-scale manufacturing plan
- Offshore site determination and CPT investigation
- Anchor design and fabrication
- Anchor installation demonstration

- Anchor pull test demonstration

Through completion of these activities and witnessing by ABS, Triton will complete the NTQ process and receive an Operational Statement of Maturity.

3 References

American Bureau of Shipping (2017) Guidance Notes of New Technology Qualification. Available at https://ww2.eagle.org/content/dam/eagle/rules-and-guides/current/other/272_qualifyingnewtechnologies/NTQ_GN_e-Apr17.pdf

Appendix A. ABS NTQ Statements of Maturity

Included in this appendix are the statements of maturity (SOM) from ABS for each stage completed during the NTQ process.

In order are:

1) Feasibility Stage SOM

2) Concept Verification Stage SOM

3) Prototype Validation Stage SOM

4) Systems Integration Stage Letter of Intent to issue SOM

A.1 Feasibility Stage SOM

Task – T2140798
Qualifying New Technologies
Helical Anchor Group Installation System (HAGIS)

ABS Statement of Maturity for Feasibility Stage

Attention: Zachary Miller, Triton Systems Inc. (WCN 466708)

The documents shown in the attached list (the list includes previously reviewed documents also) are reviewed in accordance with the applicable requirements of the following:

- ABS Guidance Notes on Qualifying New Technologies, 2017
- ABS Rules for Building and Classing Offshore Installations, 2018

ABS noted the proposed Helical Anchor Group Installation System (HAGIS), is at the preliminary design stage and the design requires further development, therefore this review is intended to investigate the feasibility of the HAGIS in accordance with Section 3 of the ABS Guidance Notes on Qualifying New Technologies.

Please note our review is based on the following conditions:

1. Further analyses are to be performed during next phases of the project and some of the results are to be validated by means of centrifuge and full-scale model testing before final approval of the system.
2. Comment S-008 is to be satisfactorily resolved during the next phases of the project.
3. As minimum the items listed in the attached List of Recommendations are to be addressed in the Concept Verification Stage of the process.

Subject to above conditions the Feasibility Stage of the new technology qualification process of HAGIS is considered completed.

Additionally, we have received your declaration stating that the materials used in the system indicated in the submittals are free from asbestos.

For any clarifications, contact Rexie Fernando at +1 281 877 6327, (rfernando@eagle.org).

Very truly yours,

Joshua Divin
Vice President of Engineering

Electronically Signed by: Rexie Fernando

A.2 Concept Verification Stage SOM

Tasks – T2206414, T2206415
Qualifying New Technologies
Helical Anchor Group Installation System (HAGIS)

ABS Statement of Maturity for Concept Verification Stage

Attention: Zachary Miller, Triton Systems Inc. (WCN 466708)

For Concept Verification Stage the documents shown in the attached list (the list includes previously reviewed documents also) are reviewed in accordance with the applicable requirements of the following:

- ABS Guidance Notes on Qualifying New Technologies, 2017 (ABS NTQ)
- ABS Rules for Building and Classing Offshore Installations, 2018

ABS noted the proposed Helical Anchor Group Installation System (HAGIS) is at the preliminary design stage and the design requires further development, therefore this review is intended to investigate the feasibility of the HAGIS in accordance with Section 4 (Concept Verification Stage) of the ABS Guidance Notes on Qualifying New Technologies.

Please note our review is based on the following conditions:

1. Further analyses are to be performed during next phases of the project and some of the results are to be validated by means of centrifuge and full-scale model testing before final approval of the system.
2. Comments S-008, S-010, S-013 are to be satisfactorily resolved during the next phases of the project.
3. As minimum the items listed in the attached List of Recommendations are to be addressed in the Prototype Validation Stage of the process.

Subject to above conditions the Concept Verification Stage of the new technology qualification process of HAGIS is considered completed.

For any clarifications, contact Rexie Fernando at +1 281 877 6327, (rfernando@eagle.org).

Very truly yours,

Joshua Divin
Vice President of Engineering

Electronically Signed by: Rexie Fernando

A.3 Prototype Validation Stage SOM

STATEMENT OF MATURITY

ABS

Client Name: Triton Systems Inc.
Date Issued: September 29, 2022

Certificate Number: T2310509
Valid Until: September 29, 2027

TECHNOLOGY QUALIFIED

This is to certify that

Helical Anchor Group Installation System (HAGIS)

has been reviewed in accordance with the ABS *Guidance Notes on Qualifying New Technologies* [1]. The technology is validated through demonstration as being able to perform within the established performance requirements for a defined period of time in accordance with the defined performance requirements as outlined in ABS Letter Reference T2310509 dated September 29, 2022. The technology may proceed to the ***System Integration Stage***.

Description and Application: HAGIS Innovative Anchoring System for Floating Offshore Wind

Boundaries: HAGIS in sand profiles only, review is based on computer simulation

Scope of Review: Review of the documents submitted for helical anchor group installation system (HAGIS) being developed by Triton Systems for floating offshore wind applications for Prototype Validation Stage (Stage 3) requirements of the American Bureau of Shipping (ABS) New Technology Qualification (NTQ) process.

Comments/Notes: See ABS Letter Reference T2310509 dated September 29, 2022

Reference Documents:
[1] ABS *Guidance Notes on Qualifying New Technologies*

ABS shall in no event be held liable for any identified/unidentified hazardous scenarios or qualification activities associated with this technology.

Approved By:

Joshua Divin
Vice President of Engineering

A.4 Systems Integration Stage SOM

STATEMENT OF MATURITY

Client Name: Triton Systems Inc.
Date Issued: June 30, 2023

Certificate Number: T2422928

TECHNOLOGY INTEGRATED

This is to certify that

HELICAL ANCHOR GROUP INSTALLATION SYSTEM (HAGIS)

has been verified in accordance with ABS *Guidance Notes on Qualifying New Technologies* [1]. The technology has been integrated into the final system. All functional and performance requirements of the integrated system as outlined in ABS Letter Reference T2422928 dated June 30, 2023 are validated through testing. The technology is integrated and is now ready to proceed to the ***Operational Stage***.

Description and Application: HAGIS Innovative Anchoring System for Floating Offshore Wind

Boundaries: HAGIS in onshore field only, review for offshore is based on computational simulation

Scope of Review: Review of the documents for Helical Anchor Group Installation System (HAGIS), developed by Triton Systems Inc. for floating offshore wind applications. Specifically, this review pertains to the System Integration stage (stage 4) requirements within the American Bureau of Shipping (ABS) New Technology Qualification (NTQ) process.

Comments/Notes: See ABS Letter Reference T2422928 dated June 30, 2023

Reference Documents:

[1] ABS *Guidance Notes on Qualifying New Technologies*

ABS shall in no event be held liable for any identified/unidentified hazardous scenarios or qualification activities associated with this technology.

Approved By: Leile Froufe

Digitally signed by Leile Froufe
Date: 2023.07.12 13:47:31 -05'00'

Leile Froufe
Vice President of Engineering