



Project Design Basis/D1.1

WP1, T1.2

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Abbreviations

ALS		Accidental Limit State
CC		Consequence Class
COD		Codirectional
COG	.....	Center of Gravity
DLC	.....	Design Load Case
ECM	.....	Extreme Current Model
EHLW	.....	Extreme High Water Level
ELWL	.....	Extreme Low Water Level
ESS	.....	Extreme Severe Sea State
EWLR	.....	Extreme Water Level Range
EWM	.....	Extreme Wind Model
FD	.....	Floater Developer
FLS	.....	Fatigue Limit State
FOWT	.....	Floater Offshore Wind Turbine
IEA	.....	International Energy Agency
ILA	.....	Integrated Load Analysis
MIS	.....	Misalignment
MPM	.....	Most Probable Maximum
MSL	.....	Mean Sea Level
MUL	.....	Multidirectional
NCM	.....	Normal Current Model
NREL	.....	National Renewable Energy Laboratory
NSS	.....	Normal Sea State
NTM	.....	Normal Turbulence Model
NWLR	.....	Normal Water Level Range
PI	.....	Proportional Integral
RL	.....	Reference Location
RNA	.....	Rotor Nacelle Assembly
ROSCO	.....	Reference Open Source Controller
SKS	.....	Station Keeping System
SSS	.....	Severe Sea State
TLB	.....	Tension Leg Buoy
TLP	.....	Tensioned Leg Platform
TSR	.....	Tip Speed Ratio
ULS	.....	Ultimate Limit State
UNI	.....	Unidirectional
WP	.....	Work Package
WT	.....	Wind Turbine
WTG	.....	Wind Turbine Generator
H_s	.....	Significant Wave Height
T_p	.....	Peak Period

Executive Summary

This report corresponds to D1.1 '*Project design basis*' of the TAILWIND project in which research on mooring lines and anchors for floating offshore wind is being developed. The scope of the activity here reported is related to the scenarios definition, including location, floater and mooring configurations, as well as the estimation of loads expected for mooring lines and anchors in selected scenarios.

These loads in mooring lines and anchors are required for the research activity being developed in other project activities, WP2 'Mooring line technology' working on the mechanical characterisation of fibre ropes used in the mooring lines, and WP3 'Anchor technology' working on anchors and soil behaviour for anchoring design.

Maximum loads have been estimated for two different sites, three floater concepts and several mooring configurations for a set of load cases, mainly maximum thrust and extreme environmental conditions. For each configuration the floater and mooring design used correspond to a preliminary design based on basic requirements given and will undergo optimisation in a later phase of TAILWIND project. Yet loads estimation at this stage provide useful inputs for already running WP2/WP3 activities.

This report is structured in the following way:

- Reference site conditions, describing the main environmental and geotechnic characteristics of the two sites selected, namely, Utsira Nord in Norway and Provence Grand Large in south France, where different environmental and water depth conditions are considered.
- Wind turbine main characteristics are described for the different floaters, including tower, RNA, blades and controller.
- FOWT design requirements describe the main criteria considered for the preliminary floater and mooring system definition for each scenario. These requirements are related to maximum tower tilt, RNA acceleration and floater excursion.
- Scenarios are defined focusing on eight selected combinations of site, floater concept, mooring layout and mooring lines material.
- Floating units main features are described for the three platforms considered, one semisubmersible based on NAUTILUS concept, and two mooring-stabilised systems based on TLB and TLP concepts.
- Design load cases run for each scenario are described for the two sites and floater concepts. These are the load cases considered for the mooring lines and anchor maximum loads estimation, including operational and extreme conditions cases.
- Finally, design tension loads are given for fairlead and anchors positions for all the mooring lines in the selected scenarios.

1. Coordinate system and units

This subsection defines the coordinate systems, motion modes, and unit conventions used in the design and analysis of the FOWT. Clear and consistent definitions are essential for accurate communication of environmental loads, motion responses, and system behaviour. The coordinate systems for environmental conditions (waves, wind, and current) and rigid-body motion modes are presented, along with the unit system adopted throughout this document, ensuring alignment with international standards.

1.1 Environmental conditions coordinate system

Wave and wind directions are expressed as “coming from” in nautical degrees, i.e. degrees relative to true north positive clockwise. In contrast, current directions are expressed as “going to” and in nautical degrees, i.e. degrees relative to true north positive clockwise. For example, “a northerly wind (wind from the north), sets up a southerly current (flowing towards the south)”.

The coordinate system followed for the waves, current, and wind is shown in Figure 1-1. Reference is taken from North (0°), increasing clockwise. For example, a wind direction of $\alpha_{\text{Wind}}=0$ degrees indicates a wind direction coming from North. A wind direction of $\alpha_{\text{Wind}}=30$ degrees and a wave direction of $\alpha_{\text{Wave}}=60$ degrees indicate a wind-wave misalignment of $\beta=30$ degrees.

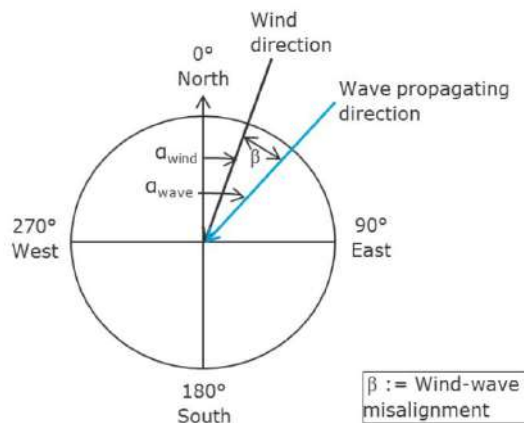


Figure 1-1: Direction of environmental loads

1.2 Rigid body-motion modes and coordinate system

The rigid-body motion modes are defined in Figure 1-2. The coordinate axis system in which loads and centres of gravity are expressed is a rotating coordinate system, parallel to the rotating axis system situated at the nacelle.

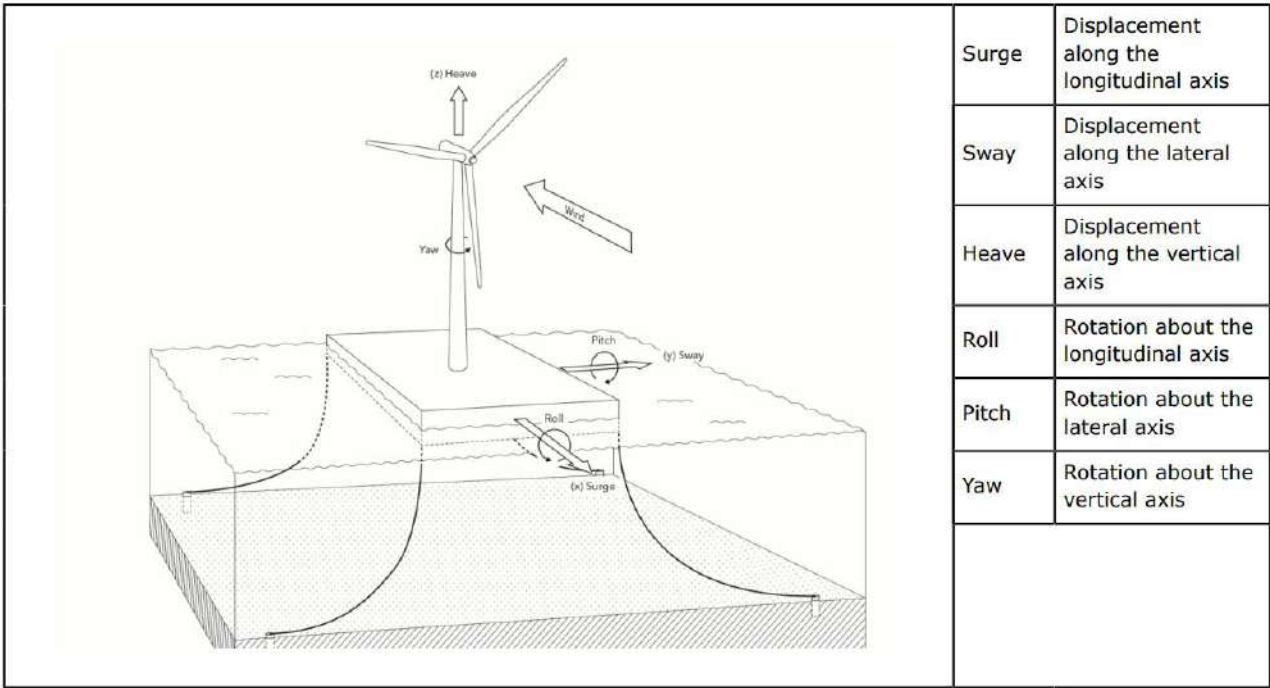


Figure 1-2: Definition of rigid-body motion modes [Source: DNV-ST-0119]

1.3 Unit system

The ISO International System of units (SI) shall be used. Angles shall be referred to in the 360 degree system.

2. Reference Site Conditions

To obtain metocean data and water depth for mooring load analysis and soil profiles for anchor sizing two reference locations (RLs) were selected:

- Reference Location 1 (RL1) – Utsira Nord in the North Sea,
- Reference Location 2 (RL2) – Provence Grand Large in the Mediterranean Sea.

The soil profiles were used in the TAILWIND Deliverable 3.1 [1] to design anchors. The mooring load analysis are used in Work Package 2 to define fibre rope testing programme.

2.1 Utsira Nord - Reference location 1 (RL1)

Utsira Nord area within the Norwegian economic zone was opened for license applications for the development of offshore wind farms in 2020. Figure 2-1 shows a map with the location of Utsira Nord. The Reference Site (RL1) Utsira Nord lies about 22 km off the Norwegian coast, covering 1,010 km². In 2022, the Norwegian government proposed a total installed capacity of 1.5 GW for Utsira Nord. The bathymetric water depth ranges between 185 m and 280 m.

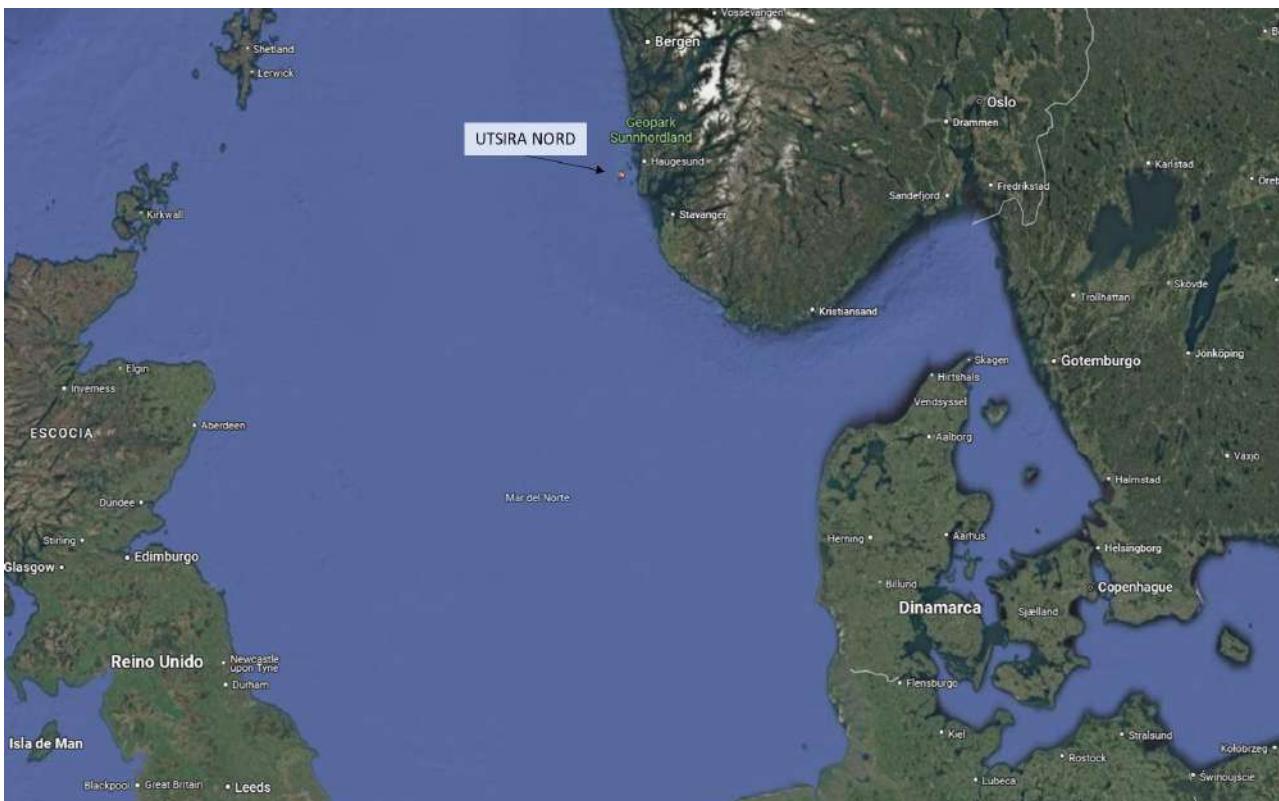


Figure 2-1: Close-up Utsira Nord [2]

2.1.1 RL1- Metocean Data for DLCs definition

For the site representative of conditions near Utsira, Norway, the main source of metocean information is the Hywind Metocean Design Basis [3]. Wind analysis therein is based on the Hirlam hindcast model, covering 1957-2002 and calibrated with on-site measurements at Utsira from 1991 to 2001. Wave data are based on the WAM model with some correction for shadow effects from neighbouring islands.

Significant additional information was derived from an analysis of NORA10 data, covering the same area for the period 1957 to 2013. While this dataset tends to underestimate extreme wind speeds in the region, it was carefully utilized for specific purposes. Its primary application was to define the 50-year wave height conditional on wind speeds close to the turbine's nominal wind speed (severe sea-state for winds near 11 m/s at hub height) and to generate time series for real storm events. For these applications, the wind direction data from NORA10 provided more realistic time series compared to standard normative defaults. However, wind speed values were adjusted to align with extreme wind speeds consistent with the Hywind Design Basis.

A brief summary of the most representative metocean conditions at the RL1 is shown below. Figure 2-2 shows the (annual) wind rose (65m above MSL) from Hirlam model for the period 1957 – 2002. The wind rose shows the percentage of observations within each 30° sector. The directions are given as a “coming from” criterion.

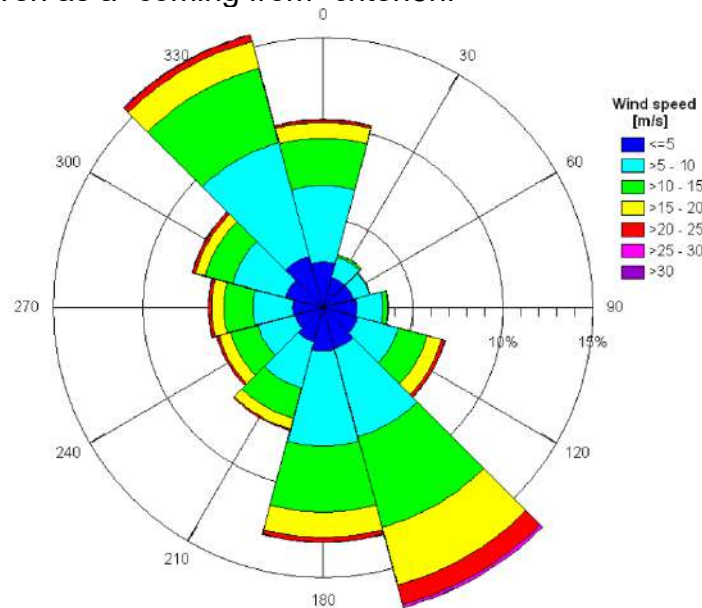


Figure 2-2: Annual wind rose (65m above MSL) for the Hywind location [3]

Figure 2-3 shows the (annual) wave rose, i.e. the sample direction distribution of significant wave height, at the Hywind location.

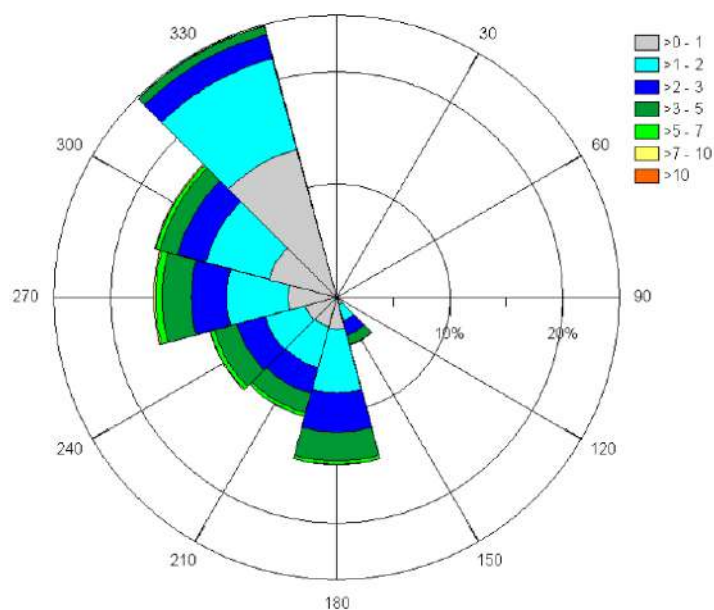


Figure 2-3: Annual wave rose for the Hywind location [3]

Figure 2-4 shows q – probability contour lines of H_s – T_p for $q = 0.63$, 10^{-1} and $2 \cdot 10^{-2}$ for omnidirectional waves. Duration of sea state is 3 hours.

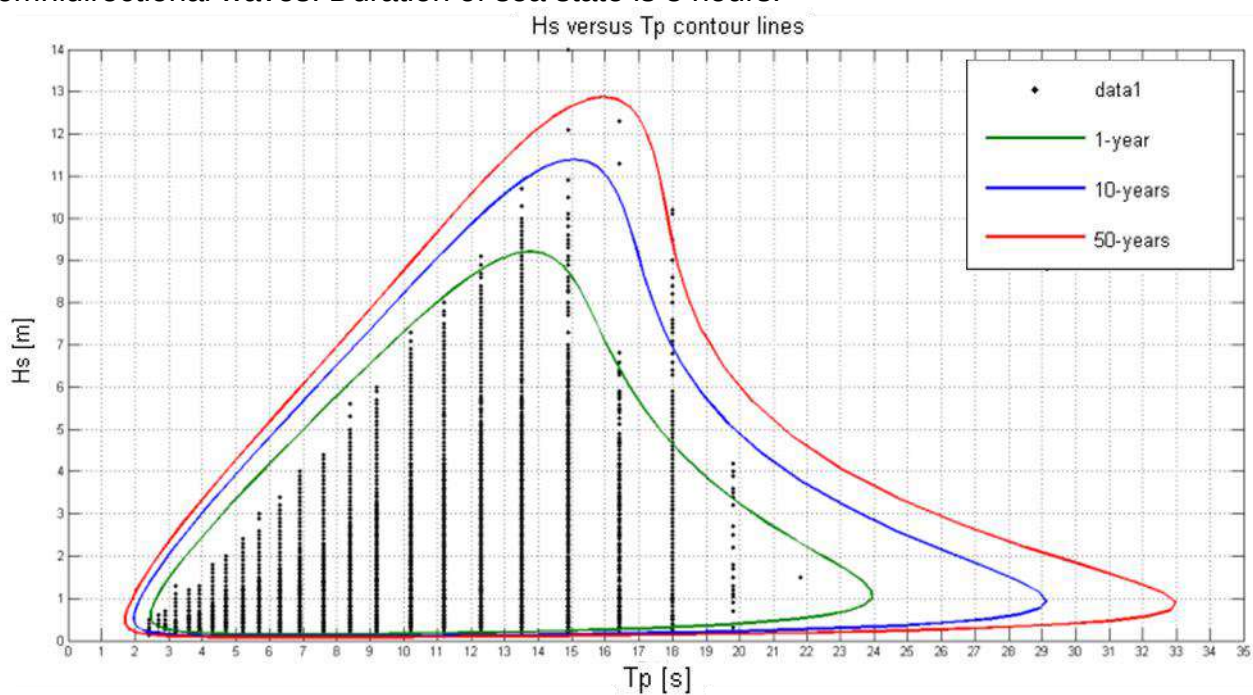


Figure 2-4: q – probability contour lines of H_s – T_p [3]

Table 2-1 shows the scatter diagram of significant wave height and spectral peak period for a return period of 50 years. The duration of sea state is 3 hours.

Table 2-1: Lumped scatter diagram

Significant wave height (top of bin)	>7													0.2%				0.30%					
	7													0.1%				0.20%					
	6.5													0.1%				0.30%					
	6													0.3%		0.2%		0.50%					
	5.5													0.6%		0.2%		0.80%					
	5													1.0%		0.2%		1.30%					
	4.5													0.3%		1.3%		1.90%					
	4													0.9%		1.6%		2.90%					
	3.5													0.1%		2.4%		1.6%		4.90%			
	3													0.2%		3.9%		1.4%		7.50%			
2.5													1.1%		2.0%		4.2%		1.8%		11.00%		
2													3.7%		3.0%		3.7%		2.6%		16.20%		
1.5													0.5%		2.7%		5.4%		2.3%		22.40%		
1	0.1%												0.4%		1.6%		3.6%		4.4%		2.3%		24.20%
0.5													0.2%		0.5%		0.8%		0.9%		0.5%		5.50%
	2	3	4	5	6	7	8	10	12	14	16	18	22	26	>26								
	Peak period top of bin																						

Current data are available from measurements at 3 depth at 59°17.40' N, 04°41.44' E west of Utsira. The measurements cover the period 27 June 1985 – 1 July 1986 at 1 hour intervals. Figure 2-5 shows current rose, i.e. sample direction distributions of current speed at 3 m depth at Utsira....

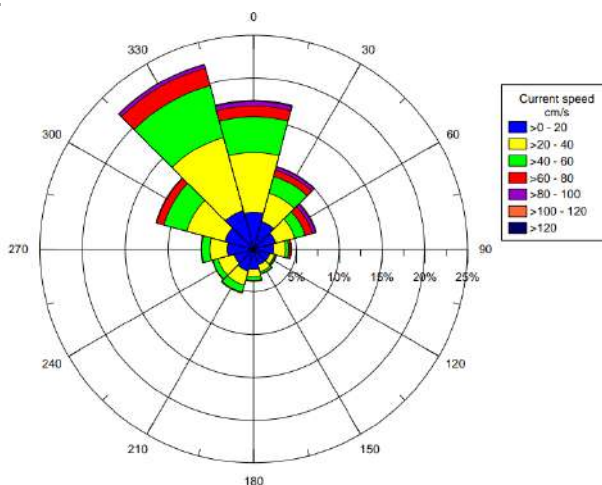


Figure 2-5: Current rose at 3 m depth at Utsira [3]

Tidal variations at the Hywind location have been computed using the NEXTRA tidal prediction system [3]. The mean spring tidal amplitude is about 30 cm. The highest tidal amplitude is about 40 cm. Storm surge data are obtained from the NEXTRA hindcast data base [3]. The storm surge with annual probability of exceedance of $2 \cdot 10^{-2}$ is found to be about 1.1 m.

2.1.2 RL1-Soil Condition and water depth

RL1 has a water depth of 265 m and features clayey soil. The soil profile was based on the Troll Field data [4] and was proven to be representative for this North Sea area by comparing it with the NGI soil profile database. Figure 2-6 shows the position of RL1 relative to the Troll Field on the Folk 16-class classification map taken from EMODnet [5].

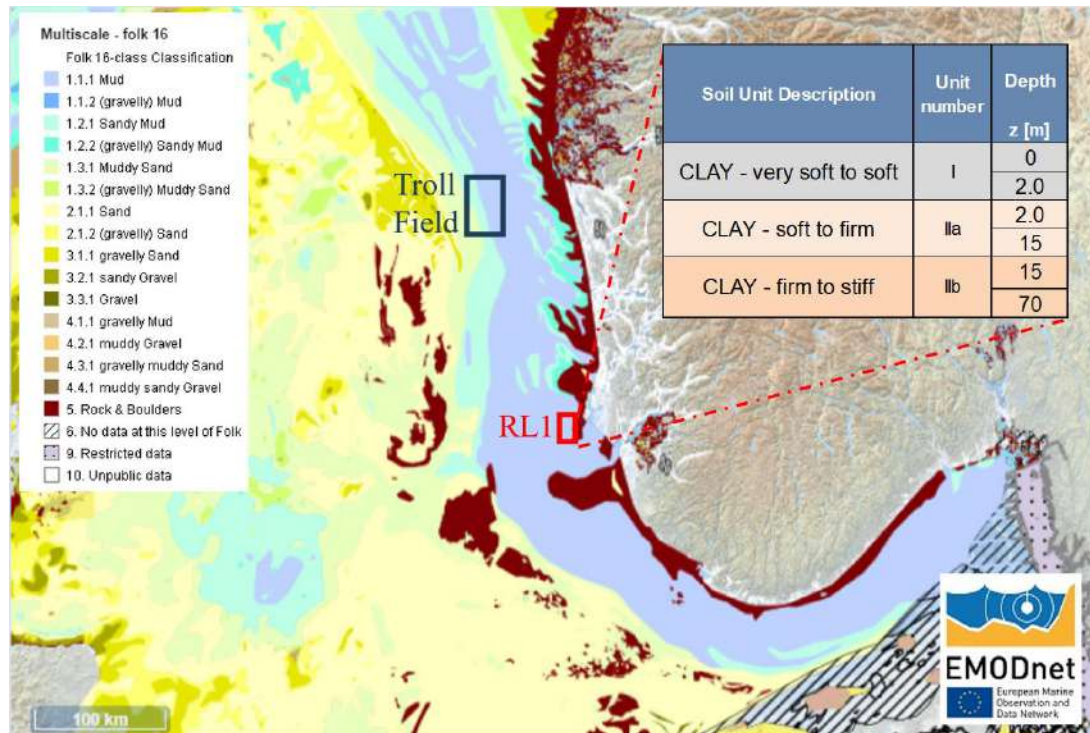


Figure 2-6: Position of RL1 relative to the Troll Field [4] on the Folk 16-class classification map taken from EMODnet [5]

RL1 consists of three layers featuring very soft to stiff clay sediments. The main properties of the RL1 profile are given in Figure 2-7 and Table 2-2.

Table 2-2: Properties of the RL1 soil profile

Soil Unit Description	Unit number	Depth	Unit weight	Best estimate cone resistance	Triax. comp. undrained shear strength	Soil sensitivity	Adhesion factor	Plasticity index	Overconsolidation ratio
		z [m]	γ [kN/m ³]	q_t [MPa]	s_{uc} [kPa]	S_t [-]	α [-]	I_p [%]	OCR [-]
CLAY - very soft to soft	I	0	17.50	0.0	0	3	0.5	20.0	1.0
		2.0	17.50	0.20	11.0				
CLAY - soft to firm	IIa	2.0	18.00	0.30	17.67				
		15	18.00	1.00	48.73				
CLAY - firm to stiff	IIb	15	18.50	1.20	62.07				
		70	18.50	4.20	194.23				

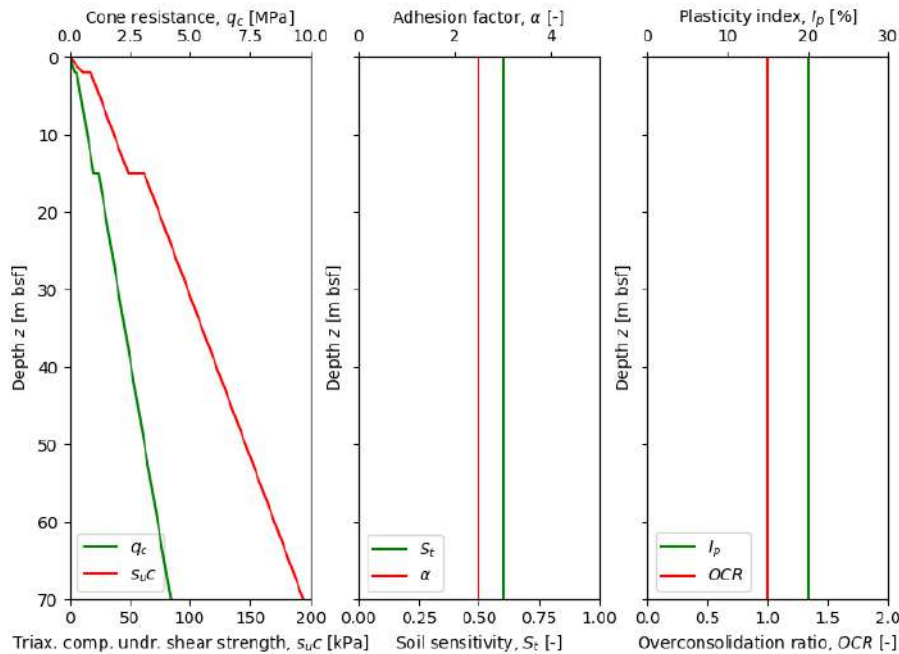


Figure 2-7: Properties of the RL1 soil profile

2.2 Provence Grand Large - Reference location 2 (RL2)

The second Reference Site (RL2) is Provence Grand Large, located in the French Mediterranean Exclusive Economic Zone (EEZ), approximately 17 km off the coast of Port-Saint-Louis-du-Rhône. This area has been identified as a pilot site for the development of floating offshore wind technology. Provence Grand Large covers an area of approximately 14 km² and is part of a broader initiative to explore the potential of floating wind farms in the Mediterranean region. The site is characterized by bathymetric depths ranging from 90 m to 120 m and benefits from consistent wind resources due to the influence of the Mistral wind. The pilot project includes the installation of three 8.4 MW turbines, demonstrating the feasibility of floating wind technology in moderate water depths.

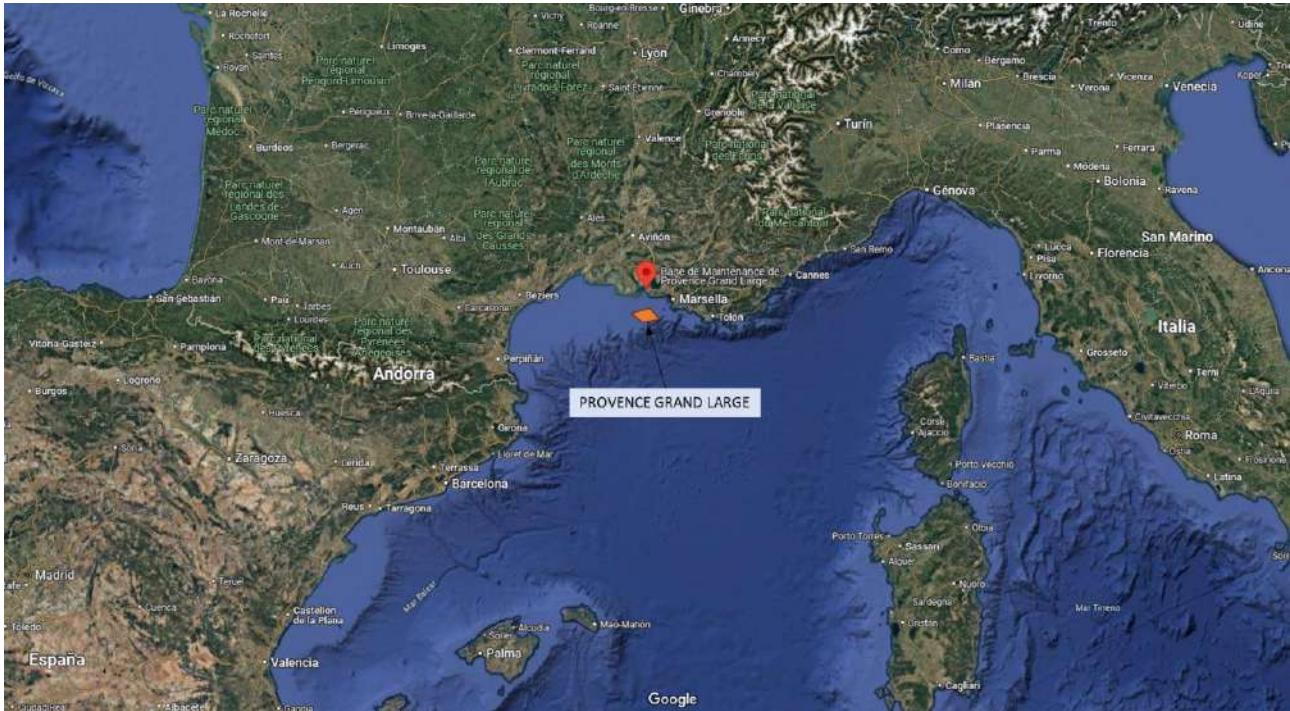


Figure 2-8 Close-up Provence Grand Large [2]

2.2.1 RL2- Metocean Data for DLCs definition

For this site, the load cases for initial sizing were specified from information from the LIFES50+ Project Design Basis [6]. As detailed therein, wave statistics are obtained from CANDHIS buoy data, and wind statistics from a combination of offshore winds from the deepwater Bouée Lion, and the closest onshore weather station onshore, near the Marignane Airport, both operated by Météo France. This was completed with the analysis from CETMEF [7] for recent water level extremes, and from SHOM's CANDHIS buoy statistics [8] for up to date conditional wave distributions.

A brief summary of the most representative metocean conditions at the RL2 is shown below. Figure 2-9 shows the wind rose from the Lion buoy record, with wind speeds extrapolated to their 120 m value with the normal wind profile. The prevailing NW and NNW pattern is very pronounced, with over 1/3 of all records within the NW and NNW sectors and nearly all wind over 20 m/s blowing from those sectors.

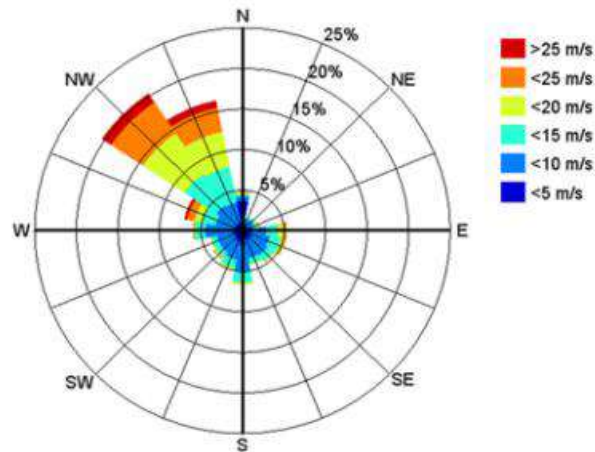


Figure 2-9: Wind Rose [3]

Figure 2-10 shows wave rose. In this area, the wind sea from the northwest sector predominates, with a low wave period, generally around 4-5 seconds, and relatively small significant wave heights. However, during strong wind gusts, this wind sea can become quite energetic, with waves exceeding 6 meters in significant height.

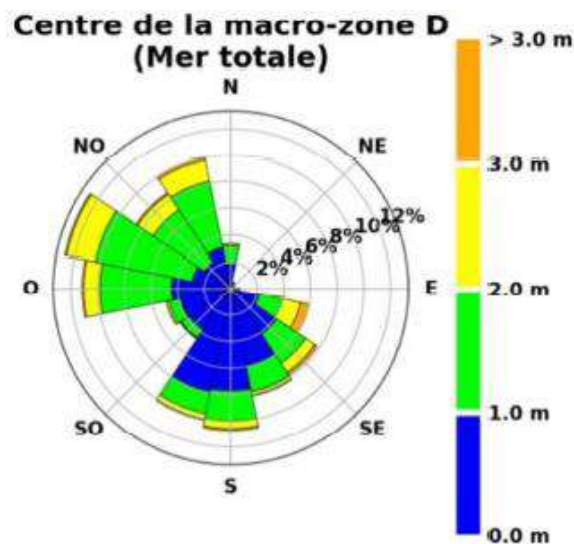


Figure 2-10: Wave Rose [8]

A weak swell from the southeast to south often adds to this wind sea. This swell generally has a peak period of 5 to 10 seconds. It may consist of residual swell from wind seas generated in the macrozones (or nearby areas) in previous days, with low significant wave heights, usually a few tens of centimeters, and, in rare cases, reaching approximately 1 meter. Swells with peak periods around 10 seconds originate from waves generated farther away in the Mediterranean and have propagated to this region. These swells typically have significant heights of a few tens of centimeters but can reach 2 to 3 meters in rare cases of winter storms.

The joint probability distribution of spectral significant wave heights and peak periods is shown in Table 2-3. To correct for uneven representation in the data record of different times

of the year, the monthly statistics were calculated first and combined to obtain the yearly averaged values.

Table 2-3: Histogram of all-seasons joint probability distribution of spectral H_s/T_p

		Peak period bin upper boundary														
		1	2	3	4	5	6	7	8	9	10	11	12	13	>13	
Hm0 bin upper boundary	0.5	0	0	3.9%	7.0%	7.0%	4.0%	4.9%	2.8%	1.0%	0.4%	0	0	0	0	31%
	1	0	0	0.5%	6.2%	9.7%	7.8%	3.8%	1.7%	0.5%	0.3%	0	0	0	0	31%
	1.5	0	0	0	0.4%	3.9%	7.8%	5.3%	1.8%	0.4%	0	0	0	0	0	20%
	2	0	0	0	0	0.6%	2.6%	5.9%	2.2%	0.4%	0	0	0	0	0	12%
	2.5	0	0	0	0	0.1%	0.4%	1.9%	2.1%	0.4%	0	0	0	0	0	5%
	3	0	0	0	0	0	0	0.3%	0.7%	0.4%	0	0	0	0	0	2%
	3.5	0	0	0	0	0	0	0	0.2%	0.2%	0	0	0	0	0	0
	4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
	>4	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
		0	0	4%	14%	21%	23%	22%	11%	3%	1%	0%	0	0	0	

As detailed in LIFES50+ Deliverable D7.2 [6] the Extreme Water Level Range (EWLR) is evaluated based on published studies of the long-term record of the tide gauge in the port of Marseilles. Tidal range is small in this part of the Mediterranean and the water level extremes are dominated by atmospheric effects. The Extreme High Water Level (EHWL) with a 50-year recurrence period is 1.13 and the Extreme Low Water Level (ELWL) with a 50-year recurrence period is -0.35.

2.2.2 RL2- Soil Condition and water depth

RL2 has a water depth of 100 m and features sandy soil. The soil profile was based on the CPT data from Gulf of Lion reported by Lafuerza et al. [9]. In the latter article location PRGL2 shows medium dense to dense sand layers for the first 25 m followed by clay layers.

In the framework of the TAILWIND Project, a requirement for the WP3 was to have uniform soil profiles – i.e. one with sandy soil only and one with clayey soil only. This requirement led to the sand layers shown in together with the position of RL2 relative to the PRGL2 location [9] on the Folk 7-class classification map taken from EMODnet [5]. The main properties of the RL2 profile are given in Table 2-4 and plotted against depth in Figure 2-12.

Table 2-4: Properties of the RL2 soil profile

Soil Unit Description	Unit number	Depth z [m]	Unit weight γ [kN/m ³]	Cone resistance q_t [MPa]	Relative density D_r [%]	Angle of internal friction ϕ [deg]	Steel-soil interface friction angle δ [deg]
Sand - Very loose to loose	I	0	20.0	0	35	28	
		2	20.0	2	35	28	
Sand - Medium dense to dense	IIa	2	20.5	10	70	33	29
		15	20.5	15	70	33	
Sand - Very dense	IIb	15	21.0	20	90	37	
		70	21.0	25	90	37	

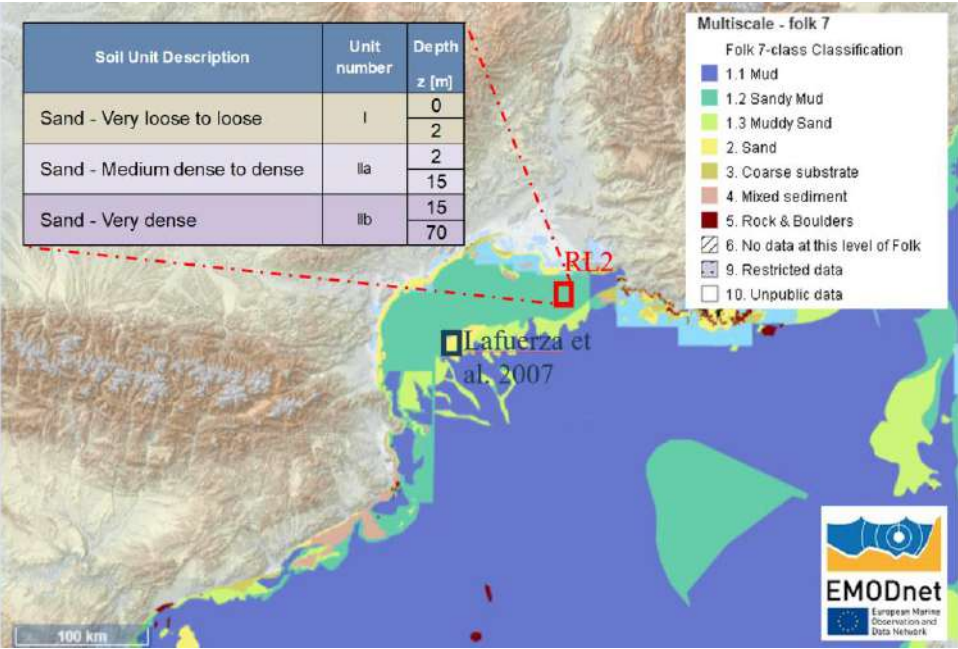


Figure 2-11: Position of RL2 relative to the PRGL2 [9] on the Folk 7-class classification map taken from EMODnet [5]

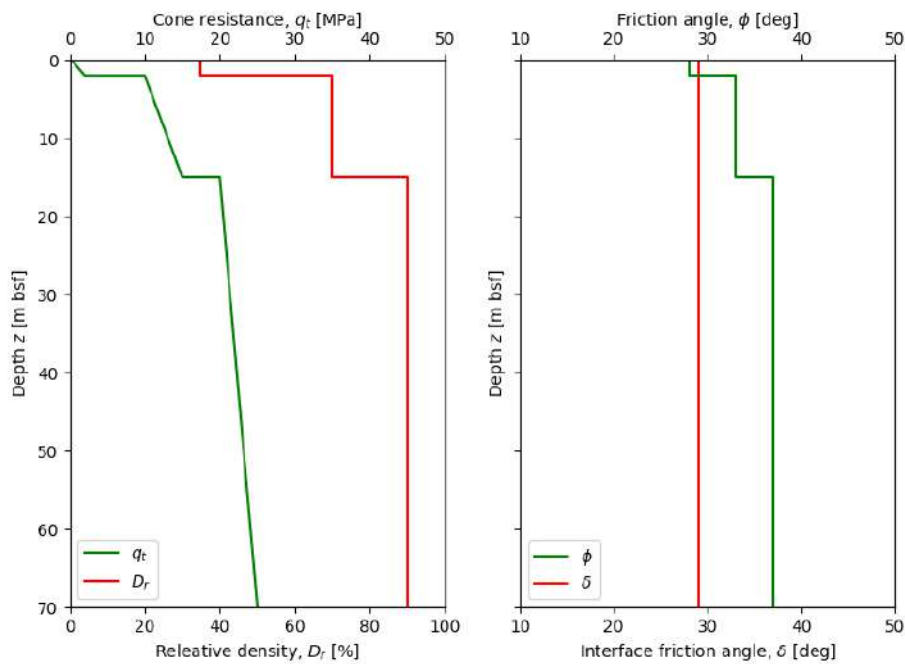


Figure 2-12 Properties of the RL2 soil profile

3. Wind Turbine Characteristics

For the TAILWIND project, the Wind Turbine (WT) used is the IEA 15MW Reference WT, developed as part of the International Energy Agency's (IEA) Wind Task 37.

In the following links, the information considered to perform the Integrated Load Analysis (ILA) with the coupled models can be found:

- **WT definition:** [nrel.gov/docs/fy20osti/75698.pdf](https://www.nrel.gov/docs/fy20osti/75698.pdf)

In this document [10], from the National Renewable Energy Laboratory (NREL), the WT definition can be found.

- **OpenFAST model data:** [GitHub - IEAWindTask37/IEA-15-240-RWT: 15MW reference wind turbine repository developed in conjunction with IEA Wind](https://github.com/OpenFAST/IEA-15-240-RWT)

The repository with the OpenFast model data for the 15MW Reference WT is available on this GitHub repository [11].

- **OrcaFlex model data:** [OrcaFlex Examples: Renewables \(orcina.com\)](https://www.orcina.com/Examples/Renewables)

The OrcaFlex model data for a 15MW semi-submersible FOWT (K03) can be found in the renewables examples on the OrcaFlex website [12].

This reference wind turbine is a Class IB direct-drive machine, with a rotor diameter of 242m and a tower height of 129.39m.

Small modifications in the nacelle mass and tower dimensions have been proposed to make the WT similar to commercial ones. These modifications are described in the following sections.

3.1 Tower

Two towers have been considered based on the type of floater. Section 3.1.1 describes the one used in tensioned concepts (Tension Leg Platform-TLP & Tension Leg Buoy-TLB), while Section 3.1.2 details the one considered for the semi-submersible platform.

3.1.1 Tower for tensioned platforms - TLB & TLP

The tower mass distribution for tensioned platforms is shown in Table 3-1.

Table 3-1: TLP&TLB -Tower mass distribution

Item	Unit	Value
Total length	m	129.386
Weight (including internals)	t	1094.994
VCG above tower bottom	m	47.617
Tower Ixx (w.r.t. cog)	t m ²	1.491E+06
Tower Iyy (w.r.t. cog)	t m ²	1.491E+06
Tower Izz (w.r.t. cog)	t m ²	1.211E+04

The tower sectional properties for tensioned platforms are shown in Table 3-2.

Table 3-2: TLP&TLB -Tower sections geometric properties

Section	t [m]	D_top [m]	D_bottom [m]	Mass [kg]	Hn [m]	Z cog [m]	Ixx[kgm ²]	Iyy [kgm ²]	Izz [kgm ²]
6-Top	0.035	5.6	5.6	49888.57	10.38	124.19	641586.43	641586.43	386267.87
5	0.030	5.6	6.0	102453.74	24	107.13	5315118.45	5315118.45	794677.35
4	0.040	6	6.8	219586.01	35	77.86	23391122.29	23391122.29	1950099.49
3	0.050	6.8	7.3	310734.92	36	42.21	35329202.00	35329202.00	3539659.26
2	0.090	7.3	7.5	292046.44	18	15.04	9783271.09	9783271.09	3796034.26
1-Bottom	0.110	7.5	7.5	120284.01	6	3.00	1182154.27	1182154.272	1642604.475

3.1.2 Tower for semi-submersible platform

The tower mass distribution for semi-submersible platform is shown in Table 3-3.

Table 3-3: Semi-submersible -Tower mass distribution

Item	Unit	Value
Total length	m	129.386
Weight (including internals)	t	1395.25
VCG above tower bottom	m	41.55
Tower Ixx (w.r.t. cog)	t m ²	1.300E+06
Tower Iyy (w.r.t. cog)	t m ²	1.300E+06
Tower Izz (w.r.t. cog)	t m ²	3.433E+04

The tower sectional properties for semi-submersible platform are shown in Table 3-4.

Table 3-4: Semi-submersible -Tower sections geometric properties

Section	t [m]	D_top [m]	D_bottom [m]	Mass [kg]	Hn [m]	Z cog [m]	Ixx[kgm ²]	Iyy [kgm ²]	Izz [kgm ²]
10 - Top	0.006	6.5	10	21380.66	13	122.43	1.40E+08	1.40E+08	2.25E+05
9	0.010	10	10	31787.92	13	109.89	1.49E+08	1.49E+08	7.93E+05
8	0.010	10	10	56798.82	13	96.89	1.75E+08	1.75E+08	1.42E+06
7	0.026	10	10	85929.39	13	83.89	1.56E+08	1.56E+08	2.14E+06
6	0.028	10	10	117777.00	13	70.89	1.05E+08	1.05E+08	2.93E+06
5	0.046	10	10	150846.61	13	57.89	4.43E+07	4.43E+07	3.74E+06
4	0.049	10	10	184147.91	13	44.89	6.93E+06	6.93E+06	4.56E+06
3	0.067	10	10	216999.32	13	31.89	2.60E+07	2.60E+07	5.35E+06
2	0.070	10	10	249292.51	13	18.89	1.35E+08	1.35E+08	6.15E+06
1 - Bottom	0.087	10	10	268012.14	12.39	6.19	3.42E+08	3.42E+08	6.58E+06

Auxiliar equipment located along the tower sections is represented by a single mass point of 120 t, located 44.74 m above the tower bottom.

3.2 RNA

In the 14-15 MW commercial WTs, the ratio of Rotor Nacelle Assembly (RNA) mass to nominal capacity has been observed to fall within the range of 50-60 t/MW. Therefore, RNA mass has been reduced by a factor of 15.77 % (see Table 3-5). This is caused by a reduction of the nacelle mass by 22.18%. The blades and hub system remain unmodified, allowing the numerical models to be used directly.

Table 3-5: Comparison of RNA masses for different commercial WT

OEM	Model	Nominal Capacity [MW]	Rotor Diameter [m]	RNA mass [t]	Capacity/Mass [t/MW]
N/A	IEA-NREL-15MW	15	242	949.78	63.32
N/A	IEA-NREL-15MW-Adapted	15	242	800	53.33

The RNA mass distribution comparison between 15 MW IEA-Adapted vs Baseline is shown in Table 3-6.

Table 3-6: RNA mass distribution comparison: Baseline vs Adapted

Item	15 MW IEA- Baseline	15 MW IEA -Adapted
RNA mass [t]	949.781	800.000
Hub mass	69.360 t	69.360 t
Nacelle mass	675.175 t	523.394 t
Blade mass (x3)	205.246 t	205.246 t
RNA cog w.r.t. tower top (x,y,z) [m]	(-6.521,-0.099,4.518)	(-6.894,-0.092,4.596)
RNA Ixx (wrt cog) [t·m ²]	4.78E+05	3.584E+05
RNA Iyy (wrt cog) [t·m ²]	3.15E+05	1.927E+05
RNA Izz (wrt cog) [t·m ²]	3.16E+05	1.919E+05

Table 3-7 shows the general properties of the proposed RNA.

Table 3-7: RNA main properties description

	Value	Units
Rated power	15	[MW]
Rotor orientation	Upwind	[-]
No. of blades	3	[-]
Rotor diameter	242	m
Cut in wind speed	3.0	[m/s]
Nominal wind speed	10.66	[m/s]
Cut out wind speed	25.0	[m/s]
RNA Mass	800	[t]
RNA Center of gravity		
X-CoG w.r.t. tower top	-6.894	[m]
Y-CoG w.r.t. tower top	-0.092	[m]
Z-CoG w.r.t. tower top	4.596	[m]
Second order mass moment of inertia		
I_{xx} w.r.t. CoG	3.584E+05	[t m ²]
I_{yy} w.r.t. CoG	1.927E+05	[t m ²]
I_{zz} w.r.t. CoG	1.919E+05	[t m ²]
Thrust at rated speed	2445.42	[kN]
Rotor speed range	5.00-7.56	[RPM]
Distance from yaw axis to rotor apex (OverHang)	-12.03	[m]
Vertical distance from the tower-top to the rotor shaft (Twr2Shft)	5.61	[m]
Rotor shaft tilt (ShaftTilt)	-6.00	[deg]

3.3 Blades

The blade length of this IEA Wind 15MW reference turbine is 117m with a root diameter of 5.2m and a maximum chord of 5.77m at approximately 20% span. The overall blade mass is around 65t. A complete statistical breakdown is listed in Table 3-8.

Table 3-8: Blade properties

	Value	Units
Blade length	117	[m]
Root diameter	5.20	[m]
Root cylinder length	2.34	[m]
Max chord	5.77	[m]
Max chord spanwise position	27.2	[m]
Tip prebend	4.00	[m]
Precone	4.00	[deg]
Blade mass	65.25	[kg]
Blade center of mass	26.80	[m]
Design tip-speed ratio	9.00	[-]
First flapwise natural frequency	0.555	[Hz]
First edgewise natural frequency	0.642	[Hz]
Design C_p	0.489	[-]
Design C_t	0.799	[-]
Annual energy production	77.4	GWh

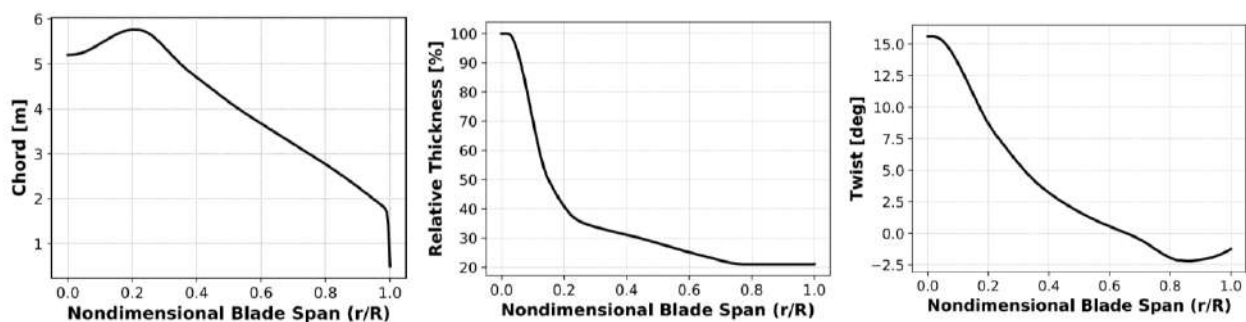


Figure 3-1: Chord, thickness and twist distributions for blade [10]

3.4 Controller

The controller (constant torque & collective pitch) used for the IEA Wind 15-MW reference wind turbine is the NREL Reference Open Source Controller (ROSCO), which was originally implemented in OpenFast, and recently validated in OrcaFlex[12]. The rotor operates with a minimum rotational speed of 5 rpm to avoid 3-period (3P) interference with the tower natural frequency, and reaches a rated rotational speed of 7.56 rpm at 10.66 m/s, resulting in a maximum nominal tip speed of 95.12 m/s. The rotor operates with a pitch setting of 0° at the design Tip Speed Ratio (TSR) but operates with positive pitch at low wind speeds to track maximum power while maintaining the minimum rotor speed. The rotor starts pitching at the rated wind speed of 10.66 m/s.

Two active Proportional Integral (PI) controllers are implemented for the generator torque and blade pitch angles. Saturation limits on rotor speeds and blade pitch angles are implemented to ensure turbine operation within the design constraints. More details regarding the controller can be found in [11].

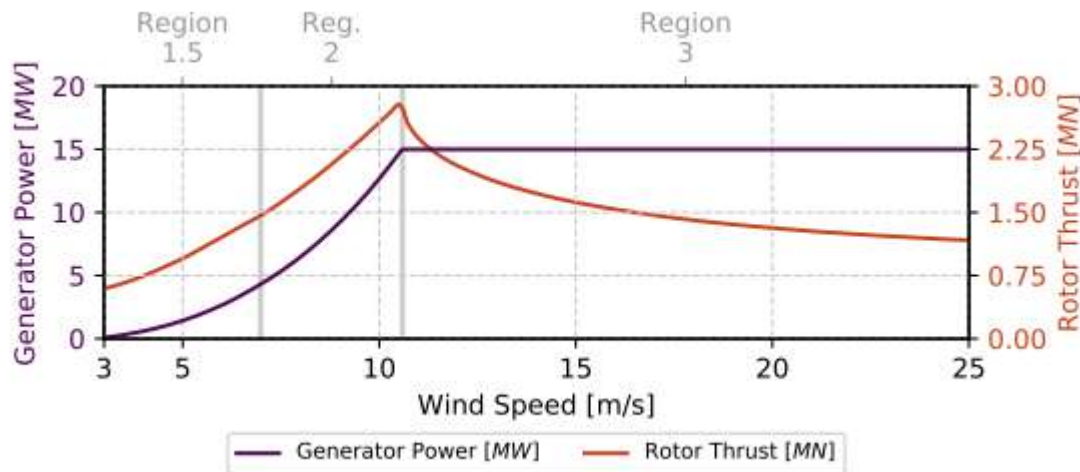


Figure 3-2: Power and thrust curve [10]

4. FOWT Design Requirements

This section outlines the key design requirements for the Floating Offshore Wind Turbine (FOWT) systems considered in this project, focusing on critical aspects necessary for ensuring structural integrity, operational performance, and compliance with industry standards. The requirements are divided into categories addressing the coordinate system and units used, floater-specific constraints, Wind Turbine Generator (WTG) limits, and mooring system specifications. Each subsection provides detailed criteria and guidance to ensure the FOWT design achieves optimal performance and meets safety thresholds under varying environmental and operational conditions.

4.1 Floater Requirements

This subsection specifies the key performance criteria and design constraints for the floater. These include natural frequency limitations to avoid resonance with turbine excitations, as well as tilt angle restrictions to ensure stability and maintain operational performance under various load cases. The requirements are designed to ensure the structural and operational reliability of the floating platform while minimizing the impact on the WTG performance.

4.1.1 Natural Frequencies

The floater natural frequencies, including floater + tower, must be outside the 1P and 3P excitation regions from the WTG, based on the WTG provided in Section 3 and considering a safety margin of 15%.

4.1.2 Mean Operational Tilt Angle at Peak Thrust

The mean tilt angle shall not exceed 5 degrees, measured at the WTG plane, during production load cases at peak thrust.

4.1.3 Extreme Tilt Angle at Peak Thrust

The maximum dynamic tilt shall not exceed 10 degrees, measured at the WTG plane, during production load cases.

4.1.4 Tilt Angle during extreme event

The maximum instantaneous heeling angle during extreme event (including shut-down) shall not exceed 15 degrees.

4.2 WTG Requirements

This subsection outlines the requirements imposed by the WTG that the floating system must meet. These criteria ensure the stability, safety, and efficient operation of the WTG under normal and extreme conditions. Key parameters include limits on horizontal and

vertical accelerations at the RNA and restrictions on yaw angles during operation. Adherence to these requirements is critical to maintaining the integrity and functionality of the WTG.

4.2.1 RNA Maximum Horizontal Acceleration

The horizontal acceleration at the RNA shall be lower than 0.3g, where g is the gravitational acceleration.

4.2.2 Maximum Vertical Acceleration

The vertical acceleration at the RNA shall be lower than 0.3g, where g is the gravitational acceleration.

4.2.3 Maximum allowable Yaw Angle

The maximum yaw angle of the floater during production load cases is 15 degrees.

4.3 Mooring Requirements

This subsection details the design requirements for the mooring system, ensuring the stability and reliability of the floating platform. Key considerations include minimizing floater excursions to maintain cable integrity, providing system redundancy to prevent failure under extreme conditions, and restricting line radii and seabed contact to ensure long-term operational safety. These requirements are essential to maintaining the platform's position and functionality throughout its service life.

4.3.1 Floater Excursion

The mooring system shall be designed to minimise the floater excursion in any direction to ensure the dynamic cable system design is optimised and integrity maintained throughout the life of field. The horizontal offset (maximum excursion from the nominal position of the floating unit) should not exceed 30% of water depth in any conditions.

4.3.2 System Redundancy

The system must be redundant, so a failure of a mooring line does not lead to failure of the remaining mooring lines under Extreme Sea States (1-year storm).

4.3.3 Mooring Radius

The maximum line radius, measured from the platform connector to the anchor location, shall not exceed 10 times the water depth.

4.3.4 Rope Contact with Seabed

No contact of any fibre rope segment with the seabed is allowed during operational cases. Contact with seabed in Extreme Sea States will be accepted depending on the number of occurrences.

5. Scenarios Definition

TAILWIND is considering three different floaters, two different sites and different materials for mooring lines. As a result of this, twenty (20) different scenarios have been defined as combinations of (i) Floater type, (ii) Location featuring soil condition, metocean data and water depth, (iii) Mooring type, and (iv) Mooring line material. Table 5-1 outlines the eight (8) scenarios selected in the project.

Table 5-1: Scenarios description

ID	Floater Type	Reefrence Location	Mooring type	Line material	Comments
3	Semi submersible	Utsira Nord (265m)	Semi-taut	Soft (Polyester)	Hybrid (chain+synthetic) line with suction anchor
5	Semi submersible	Provence Grand Large (100m)	Catenary	Soft (Polyester)	Hybrid (chain+synthetic) line with drag anchor.
6	Semi submersible	Provence Grand Large (100m)	Catenary	Steel	Full chain as baseline case with drag anchor
7	Semi submersible	Provence Grand Large (100m)	Semi-taut	Soft (Polyester)	Hybrid (chain+synthetic) line with suction anchor.
10	TLB	Utsira Nord (265m)	Taut	Hard (Dyneema)	Hybrid (steel+dyneema) line with suction anchor
10b	TLB	Utsira Nord (265m)	Taut	Hard (Dyneema)	Hybrid (steel+dyneema) line with suction anchor. Anchor sharing between floaters configuration
17	TLP	Utsira Nord (265m)	Taut	Steel	Full steel line
20	TLP	Provence Grand Large (100m)	Taut	Steel	Full steel line

From the original set of 20 scenarios, some of them were discarded due to different reasons. Semi-submersible platform configurations selected include catenary lines only in RL2 where water depth is only 100m, while in RL1 this configuration would require too long lines. In

RL1 only semi-taut mooring configuration was considered for semi-submersible platform, yet 265m water depth leads to lines long enough so that anchors can be shared with another platform (scenario 3b). Also, Semi-submersible scenarios include soft fibre materials for mooring lines (scenarios 3, 5 & 7), as well as full chain as a reference case scenario (6), while hard fibre materials are not expected to provide similar peak loads reduction in the mooring lines.

On the other hand, soft fibre materials like polyester were considered not suitable for mooring stabilised floaters, therefore only hybrid steel+dyneema or full steel lines have been run instead, which applies to TLB and TLP floaters. While in a preliminary sensitivity test hybrid line steel+dyneema configuration led to some peak loads reduction in TLB (scenarios 10&10b), in TLP it could not be seen a significant reduction and only full steel lines configuration was finally included here (scenarios 17&20), yet this issue should be further analysed later on in the project. Finally, scenarios with TLB floater in RL2 (Provence Grand Large) were not considered as water depth in RL2 is only 100m, considered too short for the TLB design here analysed.

In all selected scenarios anchors have been considered as fixed points in the numerical models, neglecting at this early project stage the soil-anchor interactions in the time domain simulations. Soil-anchor interaction will be considered in mooring and floater optimisation process at a later stage of the project.

6. Floating Units Main Features

TAILWIND will consider two floater categories: semi-submersibles (which are the most widely used) and Tensioned Platforms (TLPs & TLBs), which have particular advantages that TAILWIND will strengthen.

6.1 Semi-submersible

Nautilus semi-submersible floating platform is composed by four external columns connected at the keel plane by a x-shaped pontoon, with a central column located above the centre of the pontoon that acts as a Transition Piece (TP) connecting the tower with the floater (Figure 6-1). The WT is in a central position relative to the columns thus having a symmetric system in both x and y axes. The four external columns plus the central TP provide buoyancy and enough strength to support the turbine, and sufficient water plane area to restore forces for static and dynamic stability. The floater is anchored to the seabed by mooring lines which can have various configurations depending on the site. For the TAILWIND project Nautilus has carried out several mooring designs with different configurations for each Scenario as explained in the following Subsections. The fairlead is located below sea water level to avoid accessibility problems and reduce corrosion in the mooring lines.

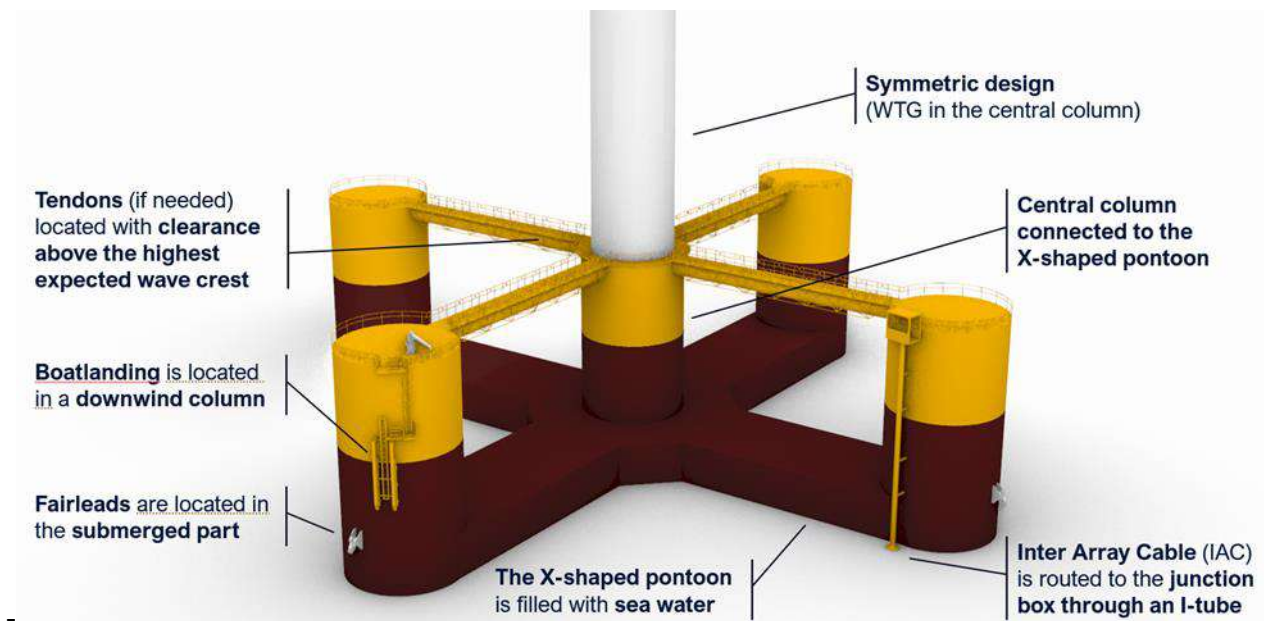


Figure 6-1: Nautilus floater 3D view

The floating platform has a x-shaped pontoon interconnecting the four external columns at their lower ends. The pontoon is filled with sea water ballast to lower the centre of gravity and improve stability. This pontoon is divided into a number of watertight tanks (passive ballast tanks) and is stiffened with equally spaced ring girders and horizontal stringers. As

observed in Figure 6-1, central part of the x-shaped pontoon is reinforced with chamfers to avoid fatigue problems at the connection point between the pontoon and the central column.

Furthermore, water ballast pumps for both pontoon and column watertight tanks are located at the central box of the pontoon (below the central column or at the chamfers) thus simplifying accessibility for O&M purposes.

The connection between the TP and the WTG is located above the splash zone, with clearance above the highest expected wave crest, to avoid damage at the connection point and turbine blades. In the same way, external column decks need to respect clearance above the highest expected wave crest.

Floater is stiffened with four horizontal tendons placed diagonally connecting the external column decks with the central one. Those are additionally used to place some walkways above so that the access to the WTG is simple. In case tendons are not necessary from the structural point of view, those can be replaced by simplified walkway supports in order to reduce primary steel weight.

The routing of the Inter Array Cable is located on one of the external columns. For this a fixed I-tube is used. The cable enters through a bellmouth or bend stiffener and is routed up near the hang-off point. The hang off system is installed in an auxiliary box located at the column deck to simplify O&M.

To have human access for O&M purposes, a boatlanding is located in a downwind external column so that the access from a vessel can be performed in a safe way. Thus, the workers can access to the column deck and pass through the walkways to the TP and to any of the additional columns.

6.1.1 Semi-submersible Floater Description

Next subsections gather main dimensions and mass properties of the floaters designed for each reference site conditions.

6.1.1.1 *Semi-submersible sizing for RL1*

Table 6-1 table gathers the main dimensions of the Nautilus floater designed for Utsira North.

Table 6-1: Nautilus floater dimensions for Utsira North

		Value	Units
Length Over All	LOA	73.25	[m]
Column distance	l_c	60	[m]
Outer Column diameter	dc_{out}	13.25	[m]
Inner Column diameter	dc_{in}	12.5	[m]
Pontoon width	w_p	13	[m]
Pontoon height	h_p	5	[m]
Pontoon chamfer distance	l_{pch}	15	[m]
Column height	h_c	28	[m]

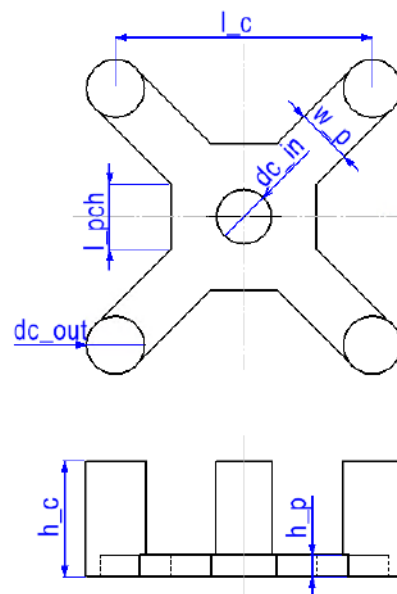


Figure 6-2: Nautilus floater main dimensions

Furthermore, mass and inertia properties of the floater are provided in Table 6-2.

Table 6-2: Floater mass and inertia breakdown for Utsira North

	Mass [t]	XG [m]	YG [m]	ZG [m]
Support substructure	3735.33	0.00	0.00	8.43
<i>Primary steel structure</i>	3522.78	0.00	0.00	8.34
<i>Coating & corrosion protection</i>	148.33	0.00	0.00	5.85
<i>Boat landing & Access system</i>	16.80	0.00	0.00	21.00
<i>Appurtenances</i>	14.70	0.00	0.00	21.00
<i>Structural foundations</i>	19.80	0.00	0.00	15.56
<i>Special structural components</i>	12.92	0.00	0.00	21.00
Electrical system	110.25	0.00	0.00	25.50
Condition monitoring system and communications (CMS)	4.20	0.00	0.00	25.50
Mechanical and auxiliary systems (MAS)	127.58	0.00	0.00	14.00
Mooring connectors	16.80	0.00	0.00	7.00
General outfitting	54.60	0.00	0.00	21.00
Total FSS w/o Passive Ballast	4048.75	0.00	0.00	9.25
Total FSS w/ Passive Ballast	17182.67	0.00	0.00	4.68

6.1.1.2 Semi-submersible sizing for RL2

The following table gathers the main dimensions of the Nautilus floater designed for RL2 based on the main dimensions shown in Figure 6-2.

Table 6-3: Nautilus floater dimensions for RL2

		Value	Units
Length Over all	LOA	72.25	[m]
Column distance	l_c	59.00	[m]
Outer Column diameter	dc_out	13.25	[m]
Inner Column diameter	dc_in	12.50	[m]
Pontoon width	w_p	13.00	[m]
Pontoon height	h_p	5.00	[m]
Pontoon chamfer distance	l_pch	15.00	[m]
Column height	h_c	23.00	[m]

Furthermore, mass and inertia properties of the floater are provided in the following table:

Table 6-4: Floater mass and inertia breakdown for RL2

	Mass [t]	X _G [m]	Y _G [m]	Z _G [m]
Support substructure	3410.84	0.00	0.00	6.92
<i>Primary steel structure</i>	3198.29	0.00	0.00	6.72
<i>Coating & corrosion protection</i>	148.33	0.00	0.00	5.85
<i>Boat landing & Access system</i>	16.80	0.00	0.00	21.00
<i>Appurtenances</i>	14.70	0.00	0.00	21.00
<i>Structural foundations</i>	19.80	0.00	0.00	15.56
<i>Special structural components</i>	12.92	0.00	0.00	21.00
Electrical system	110.25	0.00	0.00	25.50
Condition monitoring system and communications (CMS)	4.20	0.00	0.00	25.50
Mechanical and auxiliary systems (MAS)	127.58	0.00	0.00	14.00
Mooring connectors	16.80	0.00	0.00	7.00
General outfitting	54.60	0.00	0.00	21.00
Total FSS w/o Passive Ballast	3724.27	0.00	0.00	7.94

Total FSS w/ Passive Ballast	16809.27	0.00	0.00	4.31
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6.1.2 Mooring Description

This section defines the main properties of the mooring systems designed for each scenario. All mooring designs are composed by four lines positioned symmetrically every 90 degrees as shown in Figure 6-3.

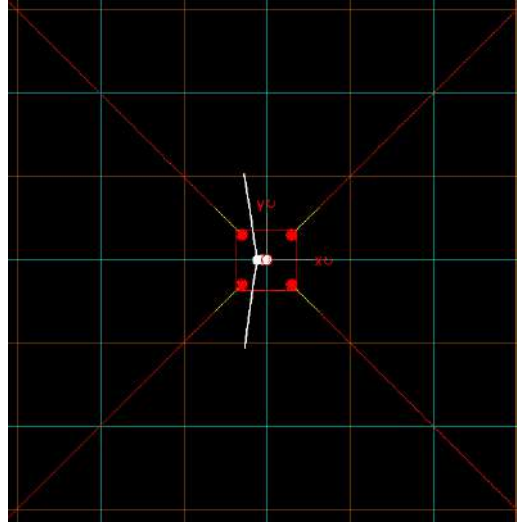


Figure 6-3: General mooring layout

6.1.2.1 Scenario 3: RL1 & Hybrid semi-taut

The proposed mooring system for this scenario is a hybrid semi-taut configuration. Each mooring line consists of three main segments: a chain section attached to the fairlead, a polyester segment forming the midsection, and a final chain section connected to the anchor. To prevent the polyester section from contacting the seabed during its service life, a buoyancy module is installed near the connection between the chain and polyester segments, close to the touchdown point.

Mooring is designed in a way that lines can be suspended to the overall length causing high vertical tensions in the anchor in harsh conditions of the service life.

Considering material properties provided by chain and fibre rope manufacturers, a mooring composed by the following components from fairlead to anchor is proposed:

- Section 1: 50 metres of 150mm diameter R3S studless chain
- Section 2: 750 metres of 226mm diameter polyester fibre rope
- Section 3: 300 metres of 150mm diameter R3S studless chain
- 20m³ buoyancy module at the chain and polyester sections connection point.

In Table 6-4 the general layout of the proposed SKS is observed.

The additional main properties of the mooring system are the following:

- Fairlead pretension = 429kN
- Anchor radial distance = 1119.65m

- Line exit angle from fairlead (wrt vertical axis) = 44°

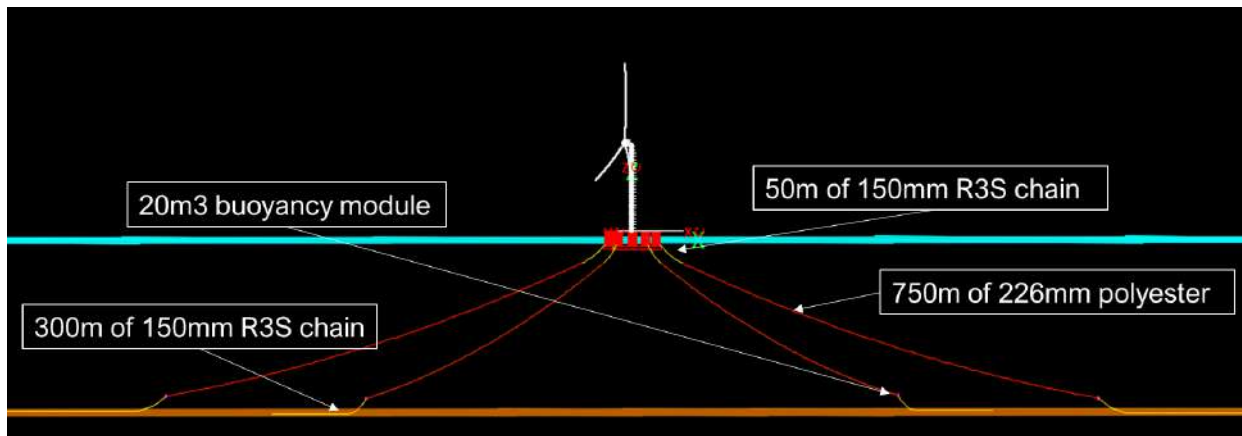


Figure 6-4: Scenario 3 SKS layout

6.1.2.2 Scenario 5: RL2 & Hybrid catenary

The proposed mooring system for Scenario 5 is a hybrid catenary configuration. The majority of the line length is composed by chains forming a catenary shape, but a short polyester section is added at the suspended part of the lines.

In this case, the mooring system is designed in a way that no significant vertical tensions occur in the anchor point.

Considering material properties provided by chain and fibre rope manufacturers, a mooring composed by the following components from fairlead to anchor is proposed:

- Section 1: 30 metres of 175mm diameter R3S studless chain
- Section 2: 70 metres of 274mm diameter polyester fibre rope
- Section 3: 577 metres of 175mm diameter R3S studless chain

In the following figure the general layout of the proposed SKS is shown:

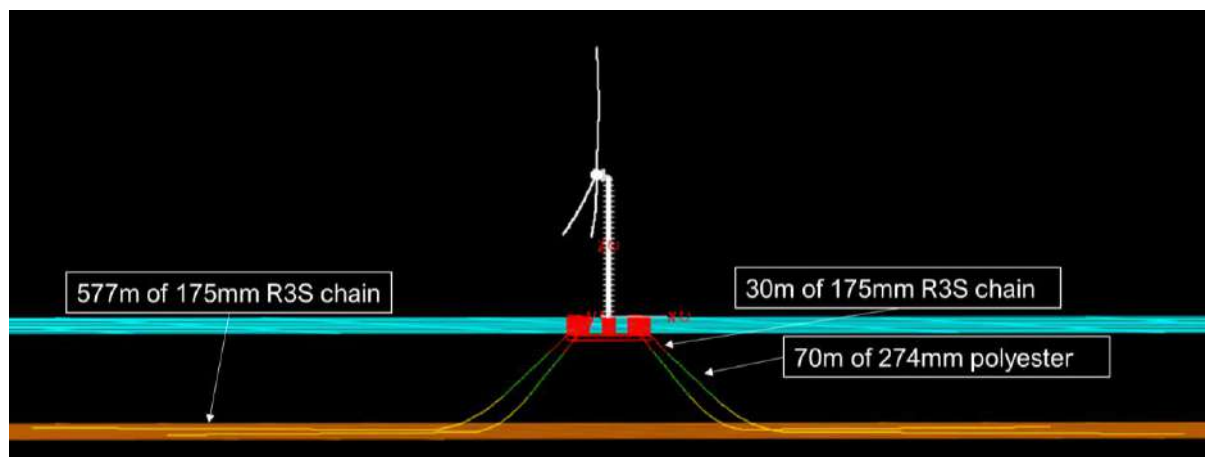


Figure 6-5: Scenario 5 SKS layout

The additional main properties of the mooring system are the following:

- Fairlead pretension = 882kN
- Anchor radial distance = 698.95m
- Line exit angle from fairlead (wrt vertical axis) = 46.15°

6.1.2.3 Scenario 6: RL2 & Full chain catenary

The proposed mooring system for Scenario 6 is a full chain catenary configuration. The overall line length is composed by chains forming a catenary shape. The mooring system is designed in a way that no significant vertical tensions occur in the anchor point.

Considering material properties provided by chain manufacturers, a mooring composed by 175mm R3S studless chain 677m length lines is proposed.

In the following figure the general layout of the proposed SKS is shown:

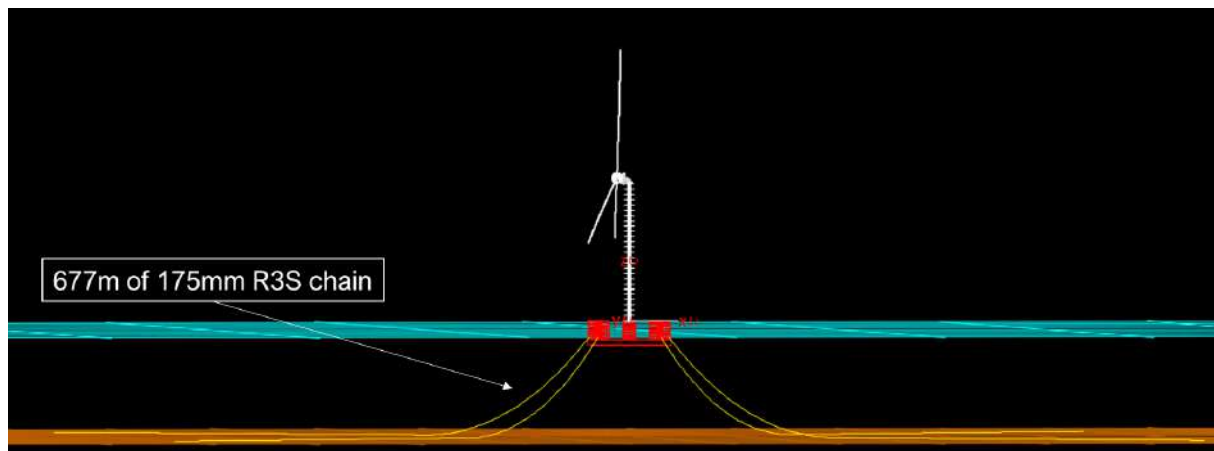


Figure 6-6: Scenario 6 SKS layout

The additional main properties of the mooring system are the following:

- Fairlead pretension = 1439kN
- Anchor radial distance = 698.95m
- Line exit angle from fairlead (wrt vertical axis) = 44.49°

6.1.2.4 Scenario 7: RL2 & Hybrid semi-taut

Same as for Scenario 3 the proposed mooring system for this scenario is a hybrid semi-taut configuration. Each mooring line consists of three main segments: a chain section attached to the fairlead, a polyester segment forming the midsection, and a final chain section connected to the anchor. To prevent the polyester section from contacting the seabed during its service life, a buoyancy module is installed near the connection between the chain and polyester segments, close to the touchdown point.

Mooring is designed in a way that lines can be suspended to the overall length causing high vertical tensions in the anchor in harsh conditions of the service life.

Compared to Scenario 3 mooring design, mooring shape, line lengths and material diameters change considerably due to the sites water depth change.

Considering material properties provided by chain and fibre rope manufacturers, a mooring composed by the following components from fairlead to anchor is proposed:

- Section 1: 50 metres of 150mm diameter R3S studless chain
- Section 2: 300 metres of 258mm diameter polyester fibre rope
- Section 3: 158 metres of 150mm diameter R3S studless chain
- 20m³ buoyancy module at the chain and polyester sections connection point.

In the following figure the general layout of the proposed SKS is observed:

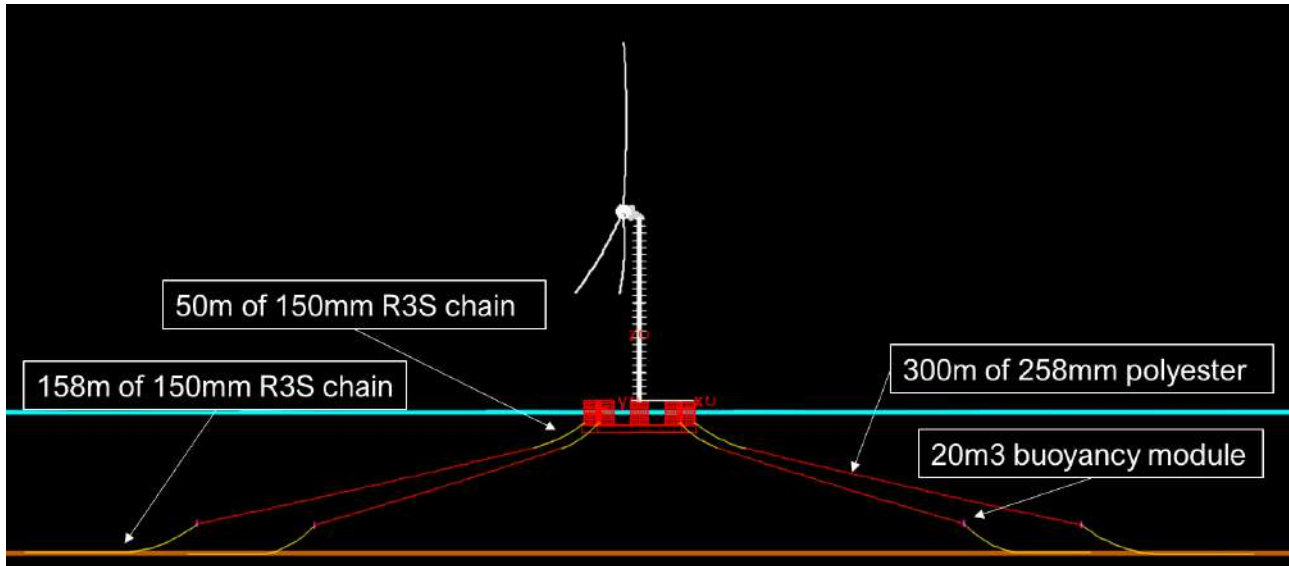


Figure 6-7: Scenario 7 SKS layout

The additional main properties of the mooring system are the following:

- Fairlead pretension = 522kN
- Anchor radial distance = 548.95m
- Line exit angle from fairlead (wrt vertical axis) = 58.81°

6.2 Tensioned Leg Buoy

The Tension Leg Buoy platform, developed by Tecalia R&I, is composed by a closed-base cylindrical steel tube. This feature gives the FOWT the required buoyancy to keep it afloat during the extremal environmental conditions. The foundation is anchored to the seabed by 6 pairs of lines, equally distributed (6x60°) along its main axis (z-axis). Mooring design is based on taut lines, connected at the top (fairlead) and in the bottom (keel) of the foundation, thus obtaining the maximum restoring arm. In the TLB system the mooring line pairs end up to one anchor only. Given the very large anchor loads, in D3.1 [[1]] one anchor per mooring line was assumed.

Regarding the structural design, at this conceptual design, the diameter of steel tube has been considered constant along its whole height. The tube wall thickness has been designed with no stiffening ring girders, paving the way for subsequent phases of structural optimization. There is not a specific TP design, but the connection between the TLB and the WTG considered keeps sufficient clearance above the highest expected wave crest to avoid damage at the connection and ensuring the safety of personnel operating the FOWT.

The mooring configuration deemed essential for design feasibility of FOWT, and therefore several inclination angles (wrt z-axis) have been considered, with flatter inclination angles proving more advantageous but impacting in the FOWT footprint radio.

TLB foundation does not require ballast (nor ballast system) for its operability, but it may be considered in the next design stages, as it could be essential for the transport and installation phase.

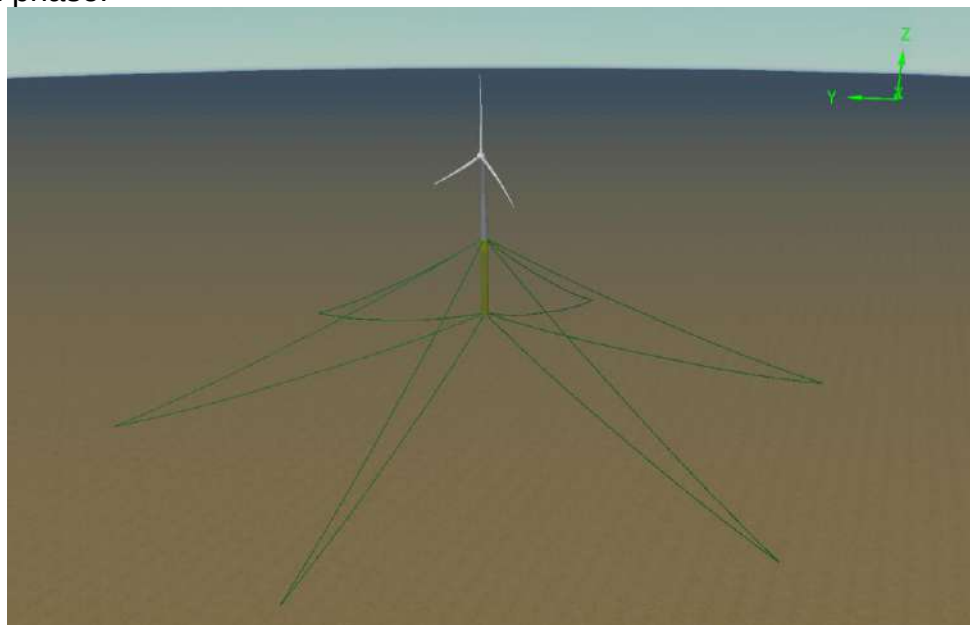


Figure 6-8: TLB floater 3D view

6.2.1 TLB Floater Description

As stated in the Section 5, TLB floater design for RL2 (Provence Grand Large) is not considered in due to major design challenges, where the floater's height is nearly equal to the considered water depth (100 m).

Table 6-5 gathers the main dimensions of the TLB floater designed for Utsira North (RL1).

Table 6-5: TLB floater dimensions for RL1

	Value	Units
Diameter of TLB	12	[m]
TP interface level @LAT	20	[m]
TLB draft @ LAT	-105	[m]
TLB length	125	[m]
TLB primary steel weight	4,578.26	[t]
TLB VCoG@keel	59.43	[m]

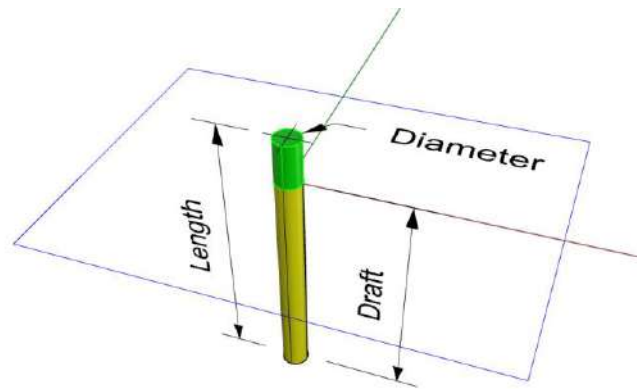


Figure 6-9: TLB floater main dimensions

Furthermore, mass and inertia properties of the floater are provided in Table 6-6.

Table 6-6: Floater mass and inertia breakdown for RL1

Mass	Mass [t]	XG [m]	YG [m]	ZG* [m]
Primary steel structure	4,578.26	0.00	0.00	59.43
Inertia (wrt CoG _i)		Ixx [t m ²]	Iyy [t m ²]	Izz [t m ²]
Primary steel structure		1.41E+07	1.41E+07	9.02E+04
FOWT		4.05E+07	4.04E+07	3.32E+05

Note: *Z=0 Keel

6.2.2 Mooring Description

This section defines the main properties of the mooring systems designed for each scenario. All mooring designs are composed by 6 pairs of lines, equally distributed (6x30°) along TLB main axis (z-axis) as showed in Figure 6-10 and Figure 6-11:

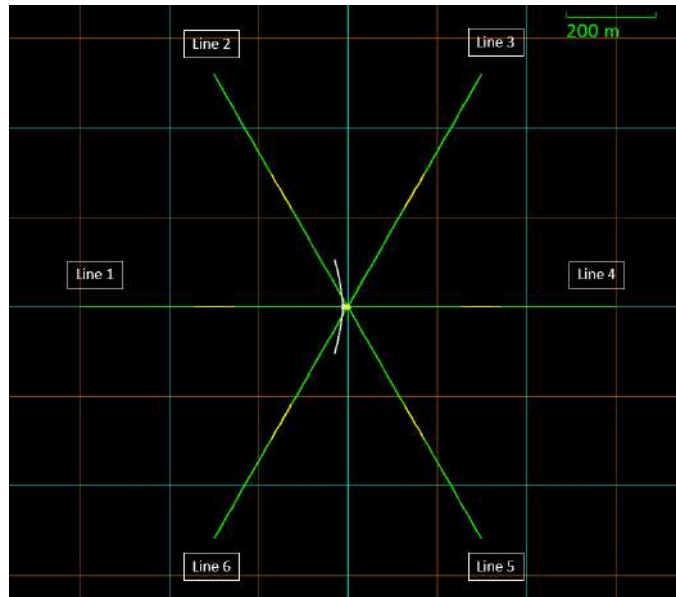


Figure 6-10: General TLB mooring layout_top view

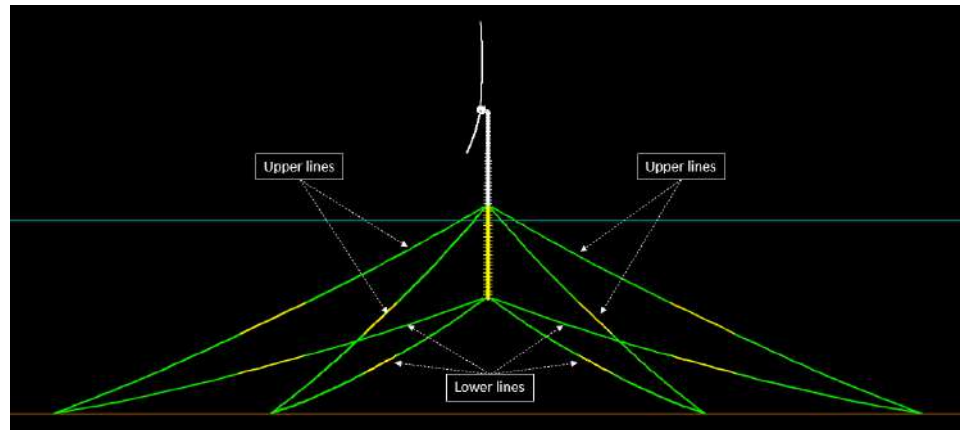


Figure 6-11: General TLB mooring layout_Elevation view

6.2.3 Scenario 10: RL1 & Dyneema

The proposed mooring system for this scenario is a hybrid taut configuration. Each mooring line consists of three main segments: a steel line section, a dyneema segment forming the midsection, and a final steel line section connected to the anchor. Additionally, mooring line pairs have been divided in two groups: those which are connected to the fairlead (notation-up lines) and those which are connected to the base of the foundation (notation-down lines). Upper lines and lower lines are connected in the same point on the seabed. Further development of lines converging at a single point on the seabed should be considered (suction buckets predilection).

Considering material properties provided by steel line and fibre rope manufacturers, a mooring composed by the following components from fairlead to anchor is proposed:

- Upper lines configuration:
 - Total line length: 657.24 m
 - Section 1: 279.62 m of 273 mm diameter steel tendon
 - Section 2: 98 m of 296 mm diameter dyneema fibre rope
 - Section 3: 279.62 m of 273mm diameter steel tendon
- Lower lines configuration:
 - Total line length: 614.076 m
 - Section 1: 261.038 m of 273 mm diameter steel tendon
 - Section 2: 92 m of 296 mm diameter dyneema fibre rope
 - Section 3: 261.038 m of 273mm diameter steel tendon

In Figure 6-12 the general layout of the proposed SKS is observed.

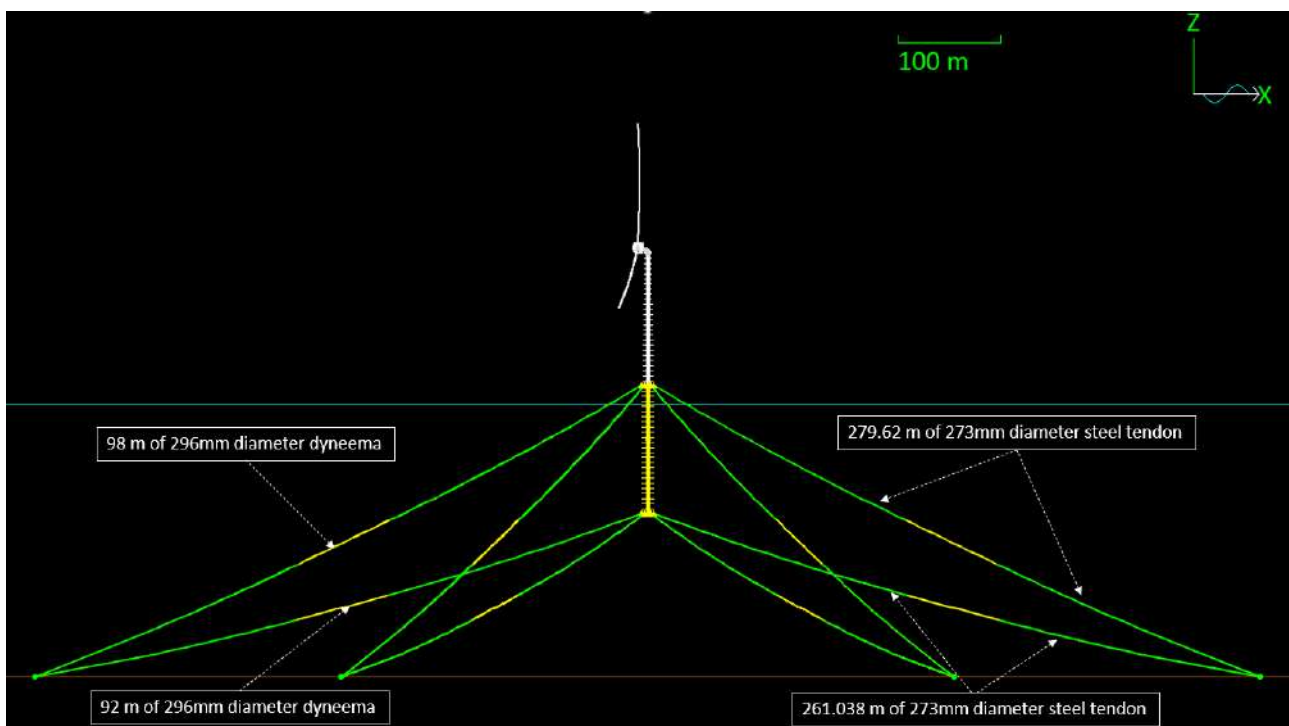


Figure 6-12: Scenario 10 SKS layout

The additional main properties of the mooring system are the following:

- Fairlead pretension upper lines= 12,124kN
- Keel pretension lower lines = 10,451kN
- Anchor radial distance = 600 m
- Line exit angle from fairlead (wrt vertical axis) = 64.60°
- Line exit angle from keel (wrt vertical axis) = 75.06°

6.2.4 Scenario 10b: RL1 & Dyneema & Anchor sharing

This scenario configuration is identical to Scenario 10, except that the anchor positions are adjusted to allow sharing between FOWT units. Properties that have been modified from Scenario 10 are:

- Upper lines configuration:
 - Total line length: 1010.74 m
 - Section 1: 426.822 m of 273 mm diameter steel tendon
 - Section 2: 157.10 m of 296 mm diameter dyneema fibre rope
 - Section 3: 426.822 m of 273mm diameter steel tendon
- Lower lines configuration:
 - Total line length: 982.207 m
 - Section 1: 414.886 m of 273 mm diameter steel tendon
 - Section 2: 152.435 m of 296 mm diameter dyneema fibre rope
 - Section 3: 414.886 m of 273mm diameter steel tendon

The additional main properties of the mooring system are the following:

- Fairlead pretension upper lines= 9,476kN
- Keel pretension lower lines = 8,897kN
- Anchor radial distance = 970 m
- Line exit angle from fairlead (wrt vertical axis) = 73.62°
- Line exit angle from keel (wrt vertical axis) = 80.63°

6.3 Tensioned Leg Platform

A defining characteristic of the TLP design is that the mooring lines have a high pretension due to the buoyant force that is larger than the gravitational force on the system. The tension force is always axial along the tendons and thus generates a restoring force if the turbine moves from its equilibrium position in surge, sway, and yaw. There are no hydrostatic restoring forces in these degrees of freedom, so stability is provided solely by the tendons. In general, the platform is laterally compliant in surge, sway, and yaw and may exhibit a significant range of motion in these DOFs. In heave, pitch, and roll, the motion of the platform will cause the tendons to extend or contract elastically. The stretched tendons act as springs which bring the system back to equilibrium. This gives the TLP a very high stiffness in heave, pitch, and roll due to the high stiffness of the steel material, resulting in limited motion in these DOFs. As opposed to other floating designs such as semisubmersible the TLP design provides limited hydrostatic restoring force in pitch and roll. Thus, the tendons play an especially important role in stabilizing the system against an overturning moment.

6.3.1 TLP Floater description

The TLP considered is the CT-bos floating platform developed in collaboration between DTU, BlueNewables, Tubacex, and GMC Deepwater [13]. It is a concrete TLP, symmetric about both vertical planes. Key characteristics of this floater are presented in Figure 6-15 and Figure 6-16. There are eight steel tendons which anchor the platform to the anchor embedded in the sea bed. It is important to highlight that the same floater design has been used across all scenarios, with only the station keeping system being adapted.

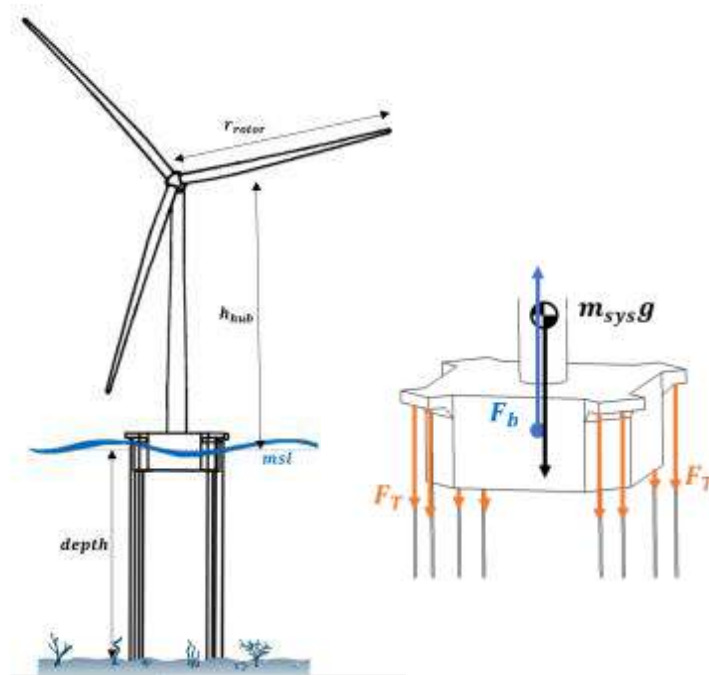


Figure 6-13: Visualisation of the CT-bos floating unit [13]

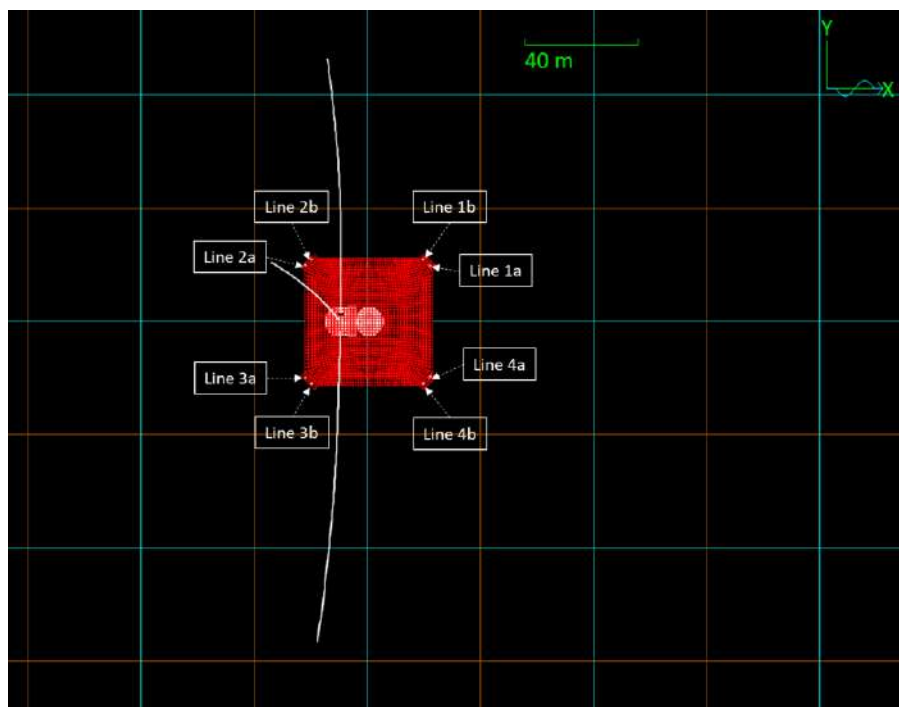


Figure 6-14: General TLP mooring layout top view

Variable	Description	Value	Unit
D_{float}	Draft below MSL	17.65	m
V_{displ}	Dispalced Water	34,981	m ³
m_{displ}	Displaced Mass	35,855	t
F_b	Buoyant Force (at MSL)	3.52e+05	kN
w_{float}	Floater Width	45	m
h_{float}	Floater Height	19.65	m
RIJ_{xx}	Radius of Gyration	15.99	m
RIJ_{yy}	Radius of Gyration	15.99	m
RIJ_{zz}	Radius of Gyration	19.40	m
QC_{11}	Quadratic Drag in Surge	432	kN/(m/s) ²
QC_{22}	Quadratic Drag in Sway	432	kN/(m/s) ²
QC_{33}	Quadratic Drag in Heave	1,115	kN/(m/s) ²
QC_{44}	Quadratic Drag in Roll	5.00E+06	(kN·m)/(rad/s) ²
QC_{55}	Quadratic Drag in Pitch	5.00E+06	(kN·m)/(rad/s) ²
QC_{66}	Quadratic Drag in Yaw	2.90E+07	(kN·m)/(rad/s) ²

Figure 6-15: Floater properties (Table A.5 from [13])

Variable	Description	Value	Unit
-	Number of tendons	8	-
-	Material	Steel Rod	-
A_{line}	Cross Section Area	0.0586	m ²
C_M	Added Mass Coefficient	1.092e+02	N/m/(m/s) ²
$C_{D,p}$	Drag Coefficient, perpendicular	1.553e+02	N/m/(m/s) ²
$C_{D,l}$	Drag Coefficient along the element	1.553e+02	N/m/(m/s) ²
E	Elastic Modulus	212	GPa
F_s	Yield Strength	758.4	MPa
F_u	Yeild Force (per Tendon)	44.4	MN
m_{air}	Mass Distribution in Air	459.7	kg/m
m_{water}	Mass Distribution in Water	399.7	kg/m
OD	Outer Diameter	0.273	m
d_{line}	Fairlead Connection ¹	21.7, 23.7	m
z_{line}	Fairlead Connection (from MSL)	2	m
ζ_{moor}	Structural Damping	0.1%	-

Figure 6-16: TLP-General Mooring Line Properties (Table A.6 from [13])

6.3.2 Mooring Description

The next tables defines the main properties of the mooring systems designed for the TLP.

6.3.2.1 Scenario 17: RL1 & Steel

Table 6-7 shows the properties of the TLP tendons for Scenario 17.

Table 6-7: Scenario 17-Mooring Line Properties

Variable	Description	Value	Unit
$L_{line,265m}$	Stretched Length	267.12	m
$L_{0,265m}$	Unstretched Length	266.60	m
$T_{moor, 265 m}$	Pretension per tendon (at fairlead)	24,498.38	kN

6.3.2.2 Scenario 20: RL2 & Steel

Table 6-8 shows the properties of the TLP tendons for Scenario 20.

Table 6-8: Scenario 20-Mooring Line Properties

Variable	Description	Value	Unit
$L_{line,265m}$	Stretched Length	102.00	m
$L_{0,265m}$	Unstretched Length	101.85	m
$T_{moor, 265 m}$	Pretension per tendon (at fairlead)	18,679.87	kN

7. Design Load Cases

This Section presents the list of DLCs considered in the ILA for the assessment of the global floater performance and the structural integrity of the SKS in the framework of the TAILWIND project.

Table 7-1 outlines the definition of the selected DLCs, determined in accordance with DNV-ST-0119 [14] and DNVGL-ST-0427 [15]. However, as detailed in the following subsections, these have been specifically adapted to each floating unit concept and corresponding reference site.

Table 7-1: TAILWIND DLCs Overview

Design Situation	DLC	Wind turbulence model	Wind speed range	Sea state type	Wind & wave directionality	Currents	Water level
1) Power Production	1.1	NTM	$V_{in} < V_{hub} < V_{out}$	NSS	COD, UNI	NCM	MSL
	1.6	NTM	$V_{in} < V_{hub} < V_{out}$	SSS	COD, MUL	NCM	NWLR
6) Parked (standing still or idling)	6.1	EWM (turbulent)	$V_{hub} = V_{50y}$	ESS (Hs,50)	MIS, MUL	ECM ($U=U_{50}$)	EWLR

ULS cases are included and not FLS or ALS since the main objective of this activity is to provide other project activities, related to research on mooring lines and anchors, with the highest mooring lines loads expected during the platforms operation.

7.1 Semi-submersible

For each RL different DLCs have been defined depending on the metocean conditions for each site. For Utsira North RL, DLCs 1.1, 1.6 and 6.1 have been carried out while for Provence Grand Large only DLC1.6 and 6.1.

The aim of **DLC 1.1 for RL1** is to capture the dynamic behavior of the system in prevailing metocean conditions when the wind turbine is operating at the rated thrust. This helps to capture the effect of wind and current in mooring lines with sea states that are not adverse but can happen very frequently.

- Wave train 1: $H_s = 1.5$ m ; $T_p = 8$ s
- Wave train 2: $H_s = 1.5$ m ; $T_p = 21.8$ s
- Wind: rated thrust at 10.67 m/s
- Current: Normal Current Model
- Extreme Water Level Ranges: Lowest Astronomical Tide
- Yaw misalignment: +0 deg yaw error
- The waves, wind and current are always assumed co-aligned. 2 main directions have been considered:
 - In line: 45 deg - aligned with a mooring line.

- In between the lines: 0 deg – in between two mooring lines
- Simulations Length: 4 DLC combinations and 10 seeds of 3h
- Corrosion and marine growth are not considered

DLC 1.6 is defined to assess ULS of the mooring lines resulting from normal turbulence, 50-year SSS and normal current conditions. This DLC represents the most adverse condition of waves in which the wind turbine can operate with the rated thrust.

In this case, two conditions have been considered critical, on the one hand, severe metocean conditions with waves close from heave period, and on the other hand when the maximum pitch of the floater happens due to the floater diagonal length coupling with the wavelength.

- Wave: 50-year return period Severe Sea State
- Wind: Constant wind thrust = 10.67 m/s
- Current: Normal Current Model
- Extreme Water Level Ranges:
 - Highest Astronomical Tide for maximum pretension assessment.
 - Lowest Astronomical Tide for maximum wave height assessment.
- Yaw misalignment: +0 deg yaw error
- The waves, wind and current are always assumed co-aligned. 2 main directions have been considered:
 - In line: 45 deg - aligned with a mooring line.
 - In between the lines: 0 deg – in between two mooring lines
- Simulation Length: 4 DLC combinations, 10 seeds of 3h
- Corrosion and marine growth are not considered

DLC 6.1 is defined to assess ULS of the mooring lines resulting from extreme turbulence, 50-year ESS and extreme current conditions. This DLC represents the most adverse conditions to which the system can be subjected with extreme wave, wind and current conditions. The wind turbine cannot operate with those conditions.

In this case, three main conditions have been considered critical:

- When the system is subjected to sea states with the maximum wave height conditions.
- When the system is subjected to sea states which can resonate with the floater.
- When the system is subjected to maximum wind and current conditions.

The following bullet points gather all the parameters taken into account for the batch of simulations performed for DLC6.1:

- Wave: Extreme Sea State
- Wind: Extreme Wind Model
- Current: Extreme Current Model
- Extreme Water Level Ranges:
 - Highest Astronomical Tide for maximum pretension assessment.
 - Lowest Astronomical Tide for maximum wave height assessment.
- Yaw misalignment: +0 deg yaw error
- The waves, wind and current are always assumed co-aligned. 2 main directions have been considered:
 - In line: 45 deg - aligned with a mooring line.

- In between the lines: 0 deg – in between two mooring lines
- Simulation Length: 12 DLC combinations and 10 seeds of 3h.
- Corrosion and marine growth are not considered

For more details on the definition of load cases for the Nautilus semisubmersible concept, see Table 7-2 and Table 7-3.

Table 7-2: DLCs definition for Scenario 3 (RL1)

ID	DLC	Reason proposed	Hub height wind speed (m/s)	Wind direction (deg)	Wave Sig. Height(m)	Wave peak period (s)	Wave direction	Current speed surf (cm/s)	Current direction	Water level (m)
1	1.1	General behaviour in prevailing sea	10.67	Mid/0	1.5	8	COD	40	COD	0
2	1.1	General behaviour in prevailing sea	10.67	Line/45	1.5	8	COD	40	COD	0
3	1.1	Longest wave period, Hs=1.5 m	10.67	Mid/0	1.5	21.8	COD	103	COD	-0.62
4	1.1	Longest wave period, Hs=1.5 m	10.67	Line/45	1.5	21.8	COD	103	COD	-0.62
5	1.6	Max thrust resonance: mooring MBL	10.67	Mid/0	7.5	19.0	COD	103	COD	0.95
6	1.6	Max thrust resonance: mooring MBL	10.67	Line/45	7.5	19.0	COD	103	COD	0.95
7	1.6	Max pitch and prying, diagonal	10.67	Mid/0	7.3	10.3	COD	103	COD	-0.95
8	1.6	Max pitch and prying, diagonal	10.67	Line/45	7.3	10.3	COD	103	COD	-0.95
9	6.1	Storm - wave forces centric, mooring MBL	47.4	Mid/0	12.9	14.0	COD	130	COD	1.5
10	6.1	Storm - wave forces centric, mooring MBL	47.4	Line/45	12.9	14.0	COD	130	COD	1.5
11	6.1	Storm - long-swell of max Hs	47.4	Mid/0	12.9	18.2	COD	130	COD	-1.5
12	6.1	Storm - long-swell of max Hs	47.4	Line/45	12.9	18.2	COD	130	COD	-1.5
13	6.1	Storm - max wave height at resonance	47.4	Mid/0	7.5	19.0	COD	130	COD	-1.5
14	6.1	Storm - max wave height at resonance	47.4	Line/45	7.5	19.0	COD	130	COD	-1.5
15	6.1	Storm - wind/current centric, stability, excursion	53	Mid/0	7.2	18.0	COD	163	COD	-1.5
16	6.1	Storm - wind/current centric, stability, excursion	53	Line/45	7.2	18.0	COD	163	COD	-1.5
17	6.1	Storm - wind/current centric, mooring	53	Mid/0	7.2	18.0	COD	163	COD	1.5

18	6.1	Storm - wind/current centric, mooring	53	Line/45	7.2	18.0	COD	163	COD	1.5
19	6.1	Storm - wind/current centric, resonance	53	Mid/0	7.5	19.0	COD	163	COD	-1.5
20	6.1	Storm - wind/current centric, resonance	53	Line/45	7.5	19.0	COD	163	COD	-1.5

Table 7-3: DLCs definition for Scenarios 5, 6 & 7 (RL2)

ID	DLC	Reason proposed	Hub height wind speed (m/s)	Wind direction (deg)	Wave Sig. Height(m)	Wave peak period (s)	Wave direction	Current speed surf (cm/s)	Current direction	Water level (m)
1	1.6	Max thrust, MBL	10.66	NNW line	7.5	9.5	COD	0.3731	COD	1.25
2	1.6	Max thrust, MBL	10.66	NNW line	7.5	9.5	COD	0.3731	COD	1.25
3	1.6	Max thrust, shortest severe sea-state	10.66	NNW line	7.5	8.0	COD	0.3731	COD	1.25
4	1.6	Max thrust, shortest severe sea-state	10.66	NNW line	7.5	8.0	COD	0.3731	COD	1.25
5	1.6	Max thrust, longest severe sea-state	10.66	NNW line	7.5	11.0	COD	0.3731	COD	1.25
6	1.6	Max thrust, longest severe sea-state	10.66	NNW line	7.5	11.0	COD	0.3731	COD	1.25
7	6.1	Storm - wave forces centric, stability, excursion	37.6	NNW bisect	7.5	8.0	COD	1.32	COD	-0.35
8	6.1	Storm - wave forces centric, stability, excursion	37.6	NNW bisect	7.5	8.0	COD	1.32	COD	-0.35
9	6.1	Storm - wave forces centric, mooring MBL	37.6	NNW line	7.5	8.0	COD	1.32	COD	1.25
10	6.1	Storm - wave forces centric, mooring MBL	37.6	NNW line	7.5	8.0	COD	1.32	COD	1.25
11	6.1	Storm - longest swell at max Hs	37.6	NNW line	7.5	11.0	COD	1.32	COD	1.25
12	6.1	Storm - longest swell at max Hs	37.6	NNW line	7.5	11.0	COD	1.32	COD	1.25
13	6.1	Storm - diagonal prying/pitch	37.6	NNW line	7.5	10.3	COD	1.32	COD	-0.35
14	6.1	Storm - diagonal prying/pitch	37.6	NNW line	7.5	10.3	COD	1.32	COD	-0.35

15	6.1	Storm - edgewise prying/pitch	37.6	NNW edge	7.5	8.6	COD	1.32	COD	-0.35
16	6.1	Storm - edgewise prying/pitch	37.6	NNW edge	7.5	8.6	COD	1.32	COD	-0.35

7.2 Tensioned Floaters: TLP/TLB

DLC 1.1 has focused on checking springing phenomena in the TLB/TLP foundations. Therefore, two regular wave trains in combination with no wind / rated wind and no current / 50-year return period current have been considered:

- Wave train 1: $H_s = 1$ m ; $T_p = 3$ s
- Wave train 2: $H_s = 2$ m ; $T_p = 4.5$ s
- Wind: rated thrust at 10.59 m/s
- Current: Extreme Current Model
- Extreme Water Level Ranges: Lowest Astronomical Tide
- Yaw misalignment: +0 deg yaw error
- The waves, wind and current are always assumed co-aligned. 2 main directions have been considered:
 - In line, aligned with a mooring line: 0 deg for scenarios 10&10b (TLB lines L1, Figure 6-10), 45 deg for scenarios 17&20 (TLP lines L2, Figure 6-14).
 - Mid-line:
 - 30 deg in-between two mooring lines for scenarios 10&10b (TLB between lines L1 and L2)
 - 0 deg in-between two mooring lines for scenarios 17&20 (TLP between lines L2 and L3)
- Simulations Length: 4 DLC combinations and 10 seeds of 3h
- Corrosion and marine growth are not considered

DLC 1.6 has focused on checking the ULS and slack phenomena in the TLB/TLP mooring lines when turbine is producing. Offshore wind turbine shall be considered in the event of a combination with a severe sea state. Therefore, the following assumptions have been considered:

- Wave: 50-year return period Severe Sea State
- Wind: Constant wind thrust = 10.59 m/s
- Current: Extreme Current Model
- Extreme Water Level Ranges:
 - Highest Astronomical Tide for ULS assessment
 - Lowest Astronomical Tide for Slack assessment
- Yaw misalignment: +0 deg yaw error
- The waves, wind and current are always assumed co-aligned. 2 main directions have been considered:
 - In line, aligned with a mooring line: 0 deg for scenarios 10&10b (TLB lines L1, Figure 6-10), 45 deg for scenarios 17&20 (TLP lines L2, Figure 6-14).
 - Mid-line:
 - 30 deg in-between two mooring lines for scenarios 10&10b (TLB between lines L1 and L2)
 - 0 deg in-between two mooring lines for scenarios 17&20 (TLP between lines L2 and L3)

- Simulation Length: 2 DLC combinations, 10 seeds of 3h
- Corrosion and marine growth are not considered

DLC 6.1 has focused on checking the ULS and slack phenomena in the TLB/TLP mooring lines when the rotor of a parked wind turbine in stand-by mode is at standstill or idling. Therefore, the following assumptions have been considered:

- Wave: Extreme Sea State
- Wind: Extreme Wind Model
- Current: Extreme Current Model
- Extreme Water Level Ranges:
 - Highest Astronomical Tide for ULS assessment
 - Lowest Astronomical Tide for Slack assessment
- Yaw misalignment: +0 deg yaw error
- The waves, wind and current are always assumed co-aligned. 2 main directions have been considered:
 - In line, aligned with a mooring line: 0 deg for scenarios 10&10b (TLB lines L1, Figure 6-10), 45 deg for scenarios 17&20 (TLP lines L2, Figure 6-14).
 - Mid-line:
 - 30 deg in-between two mooring lines for scenarios 10&10b (TLB between lines L1 and L2)
 - 0 deg in-between two mooring lines for scenarios 17&20 (TLP between lines L2 and L3)
- Simulation Length: 4 DLC combinations and 10 seeds of 3h.
- Corrosion and marine growth are not considered

For more details on the definition of load cases for tensioned floaters, see Table 7-4 and Table 7-5.

Table 7-4: DLCs definition for Scenario 10, 10b & 17 (RL1)

ID	DLC	Reason proposed	Hub height wind speed (m/s)	Wind direction (deg)	Wave Sig. Height(m)	Wave peak period (s)	Wave direction	Current speed surf (cm/s)	Current direction	Water level (m)
1	1.1	Springing - just waves 1 m	0	0	1	3.0	COD	0	COD	-0.95
2	1.1	Springing - waves 1 m + thrust/current	Max thrust	0	1	3.0	COD	142	COD	-0.95
3	1.1	Spring - just wave 2 m	0	0	2	4.5	COD	0	COD	-0.95
4	1.1	Springing - wave 2m + thrust/current	Max thrust	0	2	4.5	COD	142	COD	-0.95
5	1.6	MBL check	Max thrust	0	7	10.1	COD	142	COD	0.95
6	1.6	Slack check	Max thrust	0	7	10.1	COD	142	COD	-0.95
7	6.1	Slack check - wave centric	47.7	0	12.9	14.0	COD	130	COD	-1.5
8	6.1	MBL check - wave centric	47.7	0	12.9	14.0	COD	130	COD	1.5
9	6.1	Slack check - wind/current centric	53	0	7.2	14.0	COD	163	COD	-1.5
10	6.1	MBL check - wind/current centric	53	0	7.2	14.0	COD	163	COD	1.5
11	1.1	Springing - just waves 1 m	0	30 or 45	1	3.0	COD	0	COD	-0.95
12	1.1	Springing - waves 1 m + thrust/current	Max thrust	30 or 45	1	3.0	COD	142	COD	-0.95
13	1.1	Spring - just wave 2 m	0	30 or 45	2	4.5	COD	0	COD	-0.95
14	1.1	Springing - wave 2m + thrust/current	Max thrust	30 or 45	2	4.5	COD	142	COD	-0.95
15	1.6	MBL check	Max thrust	30 or 45	7	10.1	COD	142	COD	0.95
16	1.6	Slack check	Max thrust	30 or 45	7	10.1	COD	142	COD	-0.95
17	6.1	Slack check - wave centric	47.7	30 or 45	12.9	14.0	COD	130	COD	-1.5
18	6.1	MBL check - wave centric	47.7	30 or 45	12.9	14.0	COD	130	COD	1.5

19	6.1	Slack check - wind/current centric	53	30 or 45	7.2	14.0	COD	163	COD	-1.5
20	6.1	MBL check - wind/current centric	53	30 or 45	7.2	14.0	COD	163	COD	1.5

Table 7-5: DLCs definition for Scenario 20 (RL2)

ID	DLC	Reason proposed	Hub height wind speed (m/s)	Wind direction (deg)	Wave Sig. Height(m)	Wave peak period (s)	Wave direction	Current speed surf (cm/s)	Current direction	Water level (m)
1	1.1	Springing - just waves 1 m	0	0	1	3.0	COD	0	COD	-0.35
2	1.1	Springing - waves 1 m + thrust/current	Max thrust	0	1	3.0	COD	0.833	COD	-0.35
3	1.1	Spring - just wave 2 m	0	0	2	4.5	COD	0	COD	-0.35
4	1.1	Springing - wave 2m + thrust/current	Max thrust	0	2	4.5	COD	0.833	COD	-0.35
5	1.6	MBL check	Max thrust	0	7.5	8.0	COD	0.833	COD	1.25
6	1.6	Slack check	Max thrust	0	7.5	8.0	COD	0.833	COD	-0.35
7	6.1	Slack check - wave centric	0.0	0	7.5	8.0	COD	0.98	COD	-0.35
8	6.1	MBL check - wave centric	0.0	0	7.5	8.0	COD	0.98	COD	1.25
9	6.1	Slack check - wind-centric	38	0	7.5	8.0	COD	0.98	COD	-0.35
10	6.1	MBL check - wind-centric	38	0	7.5	8.0	COD	0.98	COD	1.25
11	1.1	Springing - just waves 1 m	0	30 or 45	1	3.0	COD	0	COD	-0.35
12	1.1	Springing - waves 1 m + thrust/current	Max thrust	30 or 45	1	3.0	COD	0.833	COD	-0.35
13	1.1	Spring - just wave 2 m	0	30 or 45	2	4.5	COD	0	COD	-0.35
14	1.1	Springing - wave 2m + thrust/current	Max thrust	30 or 45	2	4.5	COD	0.833	COD	-0.35
15	1.6	MBL check	Max thrust	30 or 45	7.5	8.0	COD	0.833	COD	1.25
16	1.6	Slack check	Max thrust	30 or 45	7.5	8.0	COD	0.833	COD	-0.35

17	6.1	Slack check - wave centric	0.0	30 or 45	7.5	8.0	COD	0.98	COD	-0.35
18	6.1	MBL check - wave centric	0.0	30 or 45	7.5	8.0	COD	0.98	COD	1.25
19	6.1	Slack check - wind-centric	38	30 or 45	7.5	8.0	COD	0.98	COD	-0.35
20	6.1	MBL check - wind-centric	38	30 or 45	7.5	8.0	COD	0.98	COD	1.25

8. Design Tension Loads

8.1 Design tension estimation methodology

Design Tension (T_d) is estimated at a given line position (fairlead, anchor or other positions like steel-fibre sections connection) from time-domain dynamic analyses, for each load case:

- Time series of mooring line tension are calculated for ten seeds.
- A Gumbel distribution is adjusted to the maximum value from each of the simulations (10 seeds of 3 hours) performed. Most Probable Maximum (MPM) value is estimated as:

$$MPM = \mu - 0.45s,$$

μ and s are mean and standard deviation of the peaks (i.e., the maximum observed from each seed).

- The design tension is calculated as follows:

$$T_d = TC_{mean} \cdot \gamma_{mean} + TC_{dyn} \cdot \gamma_{dyn}$$

where,

TC_{mean} is characteristic mean tension

TC_{dyn} is characteristic dynamic tension estimated as $MPM - TC_{mean}$

γ_{mean} is mean tension load factor (permanent load)

γ_{dyn} is dynamic tension load factor (environmental load)

Load factors for ULS cases are given Figure 8-1 for chain and in Figure 8-2 for steel tendons.

Limit state	Load factor	Consequence class	
		1	2
ULS	γ_{mean}	1.3	1.5
ULS	γ_{dyn}	1.75	2.2
ALS	γ_{mean}	1.00	1.00
ALS	γ_{dyn}	1.10	1.25

Figure 8-1: Load factor requirements for design of catenary mooring lines (source [14])

Load factor set	Limit state	Load categories					
		G	Q	E		D	P
				Consequence class			
				1	2		
(a)	ULS	1.25	1.25	0.7 ¹⁾		1.0	0.9/1.1 ³⁾
(b)	ULS	1.0 ²⁾	1.0	1.35	1.55	1.0	0.9/1.1 ³⁾
(c)	ULS for abnormal wind load cases as defined in DNV-ST-0437	1.1	1.1	1.1	1.25	1.0	0.9/1.1 ³⁾
(d)	ALS for intact structure	1.0	1.0	1.0	1.15	1.0	1.1 ³⁾
(e)	ALS for damaged structure	1.0	1.0	1.0	1.15	1.0	1.1 ³⁾

Figure 8-2: Load factor requirements for design of steel tendons (source [14])

The ULS analysis has been performed considering that mooring line condition at the end of life is equal at the beginning of life (without considering corrosion allowance and marine growth).

The three floaters and mooring systems designed for the scenarios considered are based on a preliminary ULS load cases design, yet in a later design optimisation FLS analysis and ALS load cases should be included, for example assuming that if one mooring line is lost the floater and remaining part of the mooring system meets the ALS criterion, which is survival for at least a one-year load, so the initial undamaged mooring system is said to be redundant. As a consequence, all structural components in the station keeping system of the floating support structure, are designed to Consequence Class 1 Load factor set (b) has been considered in case of steel tendons design.

8.2 Design tension results

For each scenario the design tension values have been estimated for all load cases and all mooring lines, at fairlead and anchor positions. Full results are given in the Annex per scenario as defined in Table 5-1, and factored according to the Figure 8-1 and Figure 8-2 while here some generic conclusions are drawn.

Regarding semi-submersible platform scenarios, the highest design tension value found is around 20000 kN, always in the in-line incidence load cases, as expected. For scenario 3 (RL1) the highest mooring loads are found in the extreme wave sea state cases, while for the three scenarios (5, 6, and 7) in RL2, the highest values are found in load cases with wave short peak period, showing peak loads even higher than those with extreme wave with longer periods. There are two reasons for this: firstly, when the wave peak period is 8 seconds, the wavelength nearly matches the floater's diagonal length, causing significant pitching and consequently high peak loads. Secondly, some mooring line modes couple with incident 8 seconds wave peak period, which can also lead to higher tensions.

Comparing results from Scenario 5 and Scenario 6, both based on catenary lines, it can be observed that polyester helps to dampen peak loads for all load cases (around 8% reduction of highest design tension), so chain diameter of the chain sections could in principle be reduced.

However, in scenario 7 based on hybrid line semi-taut mooring configuration, load values are normally lower than full steel catenary chain (scenario 6), yet for few extreme load cases highest load are higher. The main reason is that in the semi-taut system mooring

configuration, unlike scenarios 5&6 based on catenary configuration, lines can be fully uplifted leading to higher peak loads.

Comparing results from both proposed semi-taut mooring systems (scenario 3 in RL1 and scenario 7 in RL2), it can be observed that design tension values are higher for RL2 scenarios despite less adverse metocean conditions. The main reason is the considerably lower water depth in RL2, which requires lower floater excursion limits.

Regarding TLB scenarios, scenario 10 with hybrid line steel+dyneema at RL1 shows design tension highest values of around 35000 kN, which occurs in the extreme environmental conditions load cases at in-line incidence direction, therefore at lines L1 according to Figure 6-10 layout. Full steel tendons configuration was also analyzed, although results are not included here, where highest design tension value was around 50000 kN, so a nearly 30% reduction is achieved including hybrid line configuration. Lines slacking risk was also reduced, although could still be visible in some punctual situation in the worst case and line. TLB scenario 10b, which is similar to scenario 10 but enlarging lines so that anchors can be shared between different TLB platforms, shows highest design tension value around 40000 kN, slightly higher than original scenario 10. Although highest tensions happen in 10b configuration, and lines are longer, it could be expected to be paid off by the possibility of sharing anchors, which will be further analyzed in TAILWIND project. In all TLB scenarios it has been assumed that upper and lower lines always share anchor for the same floater, assumption that will be analyzed in order to achieve a conclusion about its feasibility given the tension values found. Note however that in D3.1 [1] one anchor per mooring line was designed as the anchor load magnitude of two combined mooring lines was too high for a single anchor point. Some of the future TAILWIND activities will be focused on the optimisation of the TLB system, and in particular on reducing the loads and finding a good compromise between turbine nominal power, platform and station keeping system.

Finally, TLP scenarios show highest design tension values of around 50000 kN in RL1 (scenario 17) for 45 deg incident extreme loads, which can be understood as long as RL1 extreme conditions includes significant high waves, which seem to be the main driver of highest peak loads in the mooring lines. Scenario 20 in RL2 shows highest design tension values around 40000 kN, in these cases small waves with short periods show the highest loads due to springing effects in this TLP mooring system for the given set of load cases. Regarding TLP scenarios, it is to be analyzed if a pair of lines can share a unique anchor, which seems to be quite challenging as for the TLB case, given these loads values. Indeed in D3.1 [1] the load magnitude was scaled down to a nominal value to design anchors with more realistic and feasible loads. It should be noted that TLP was the least optimized platform used in the study, which is the main reason why the loads are highest.

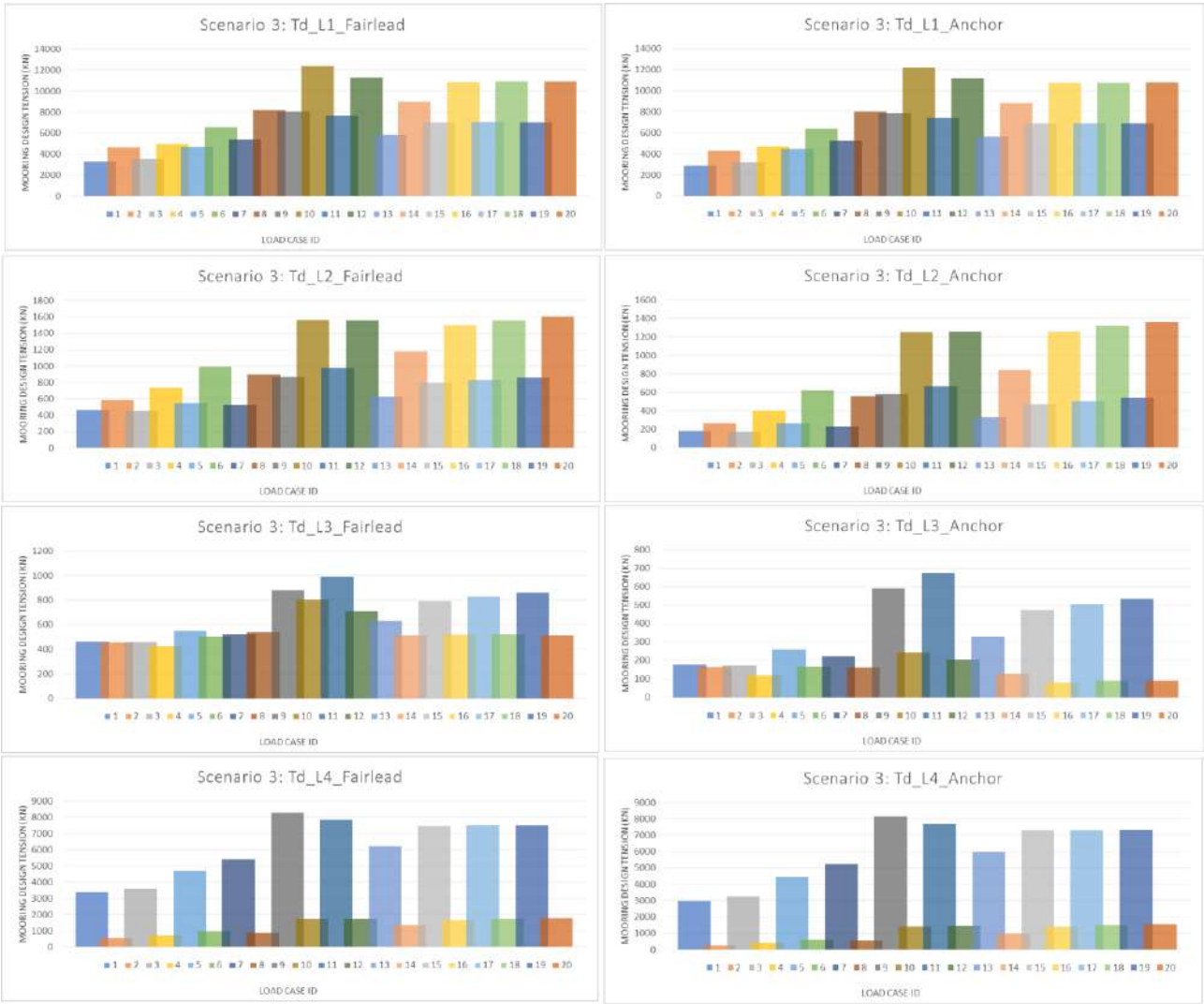
All these results are based on preliminary floater and mooring system designed at this project early stage. In a next phase mooring and floaters designs are expected to be to some extent optimized based on hybrid lines, including soil-anchor interaction for a given anchor type selected for each scenario, as well as a better characterization of fibre rope materials in hybrid lines configurations, all this part of the TAILWIND project current research activities.

References

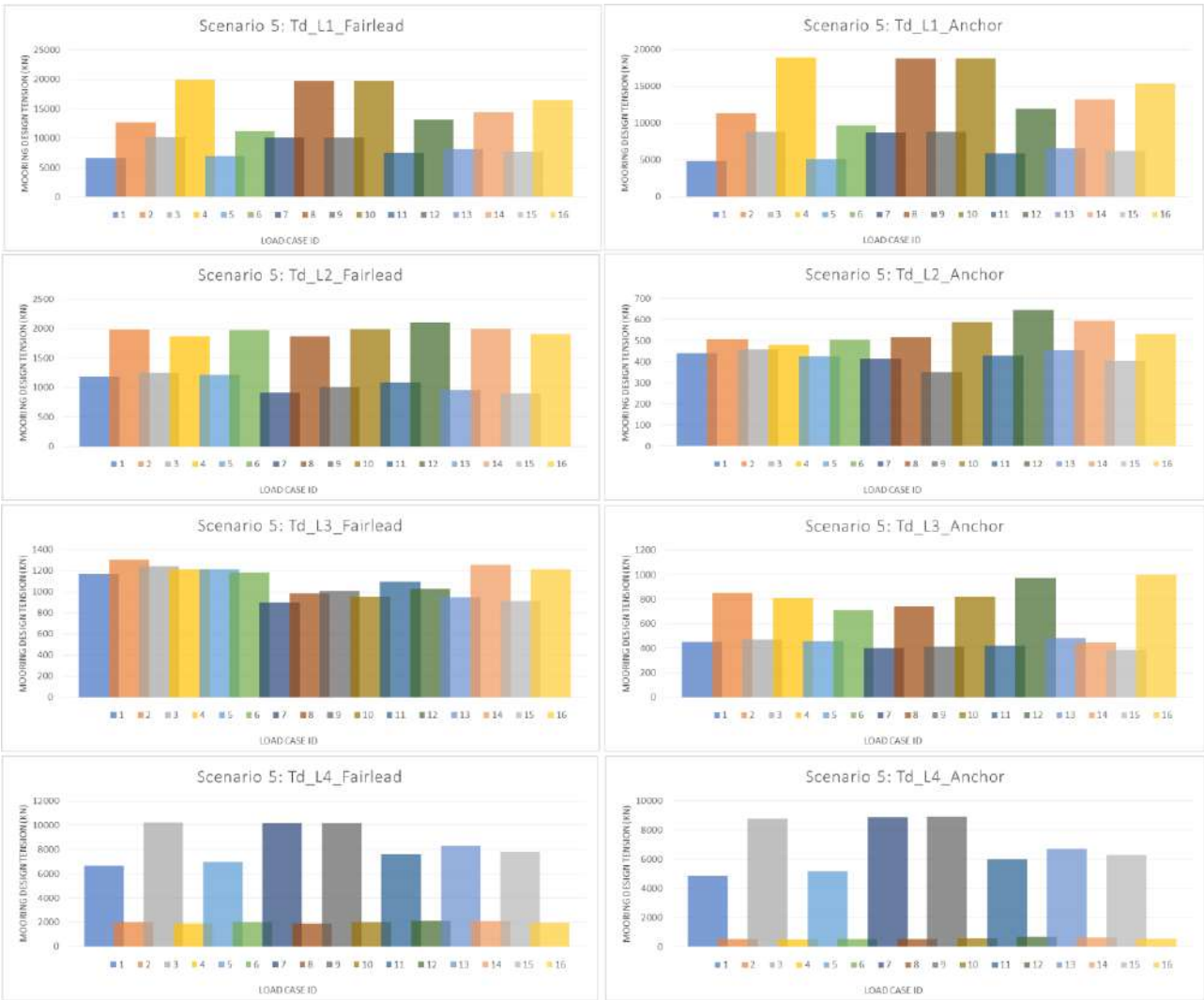
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Annex. Design tension values per scenario

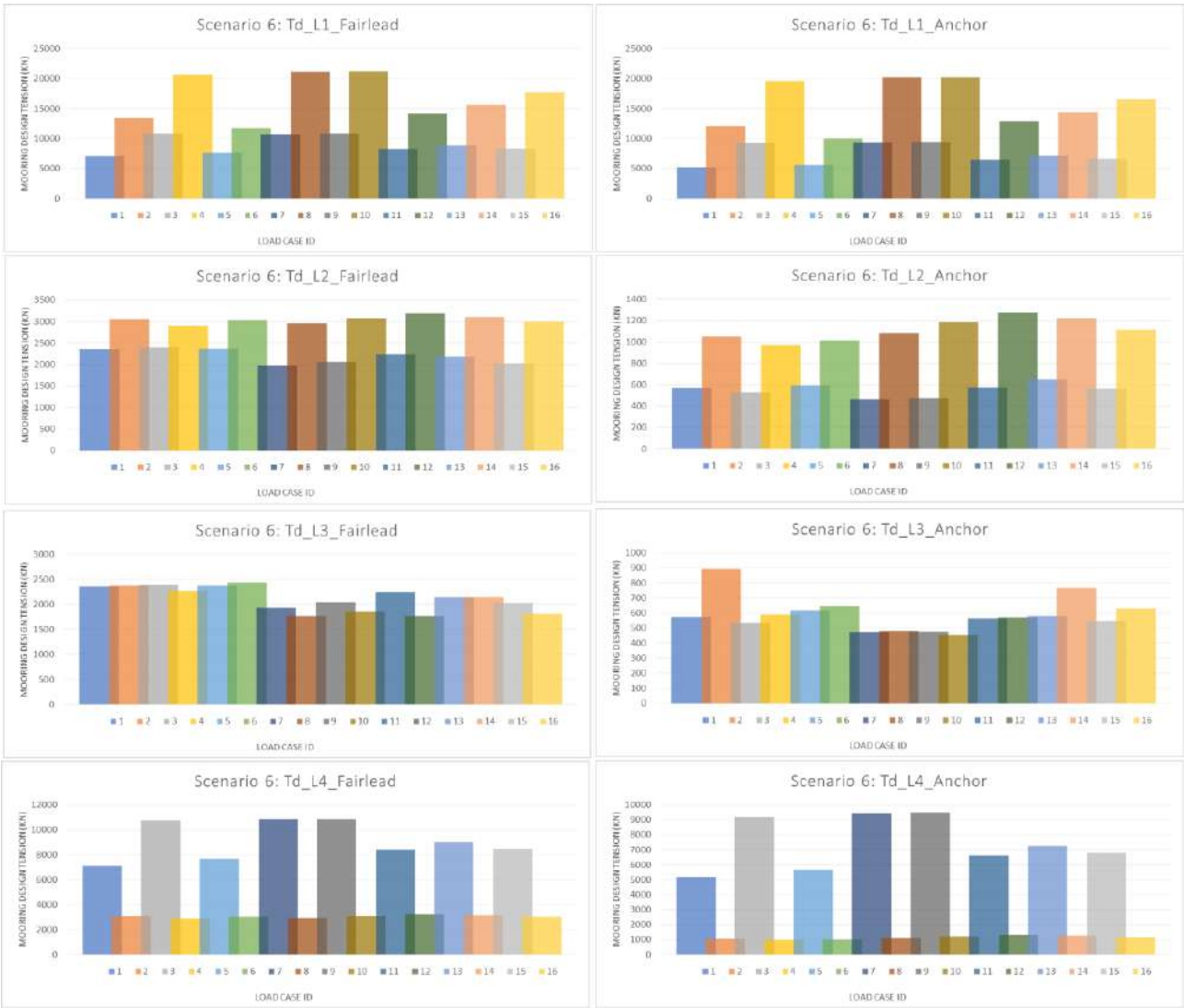
Scenario 3



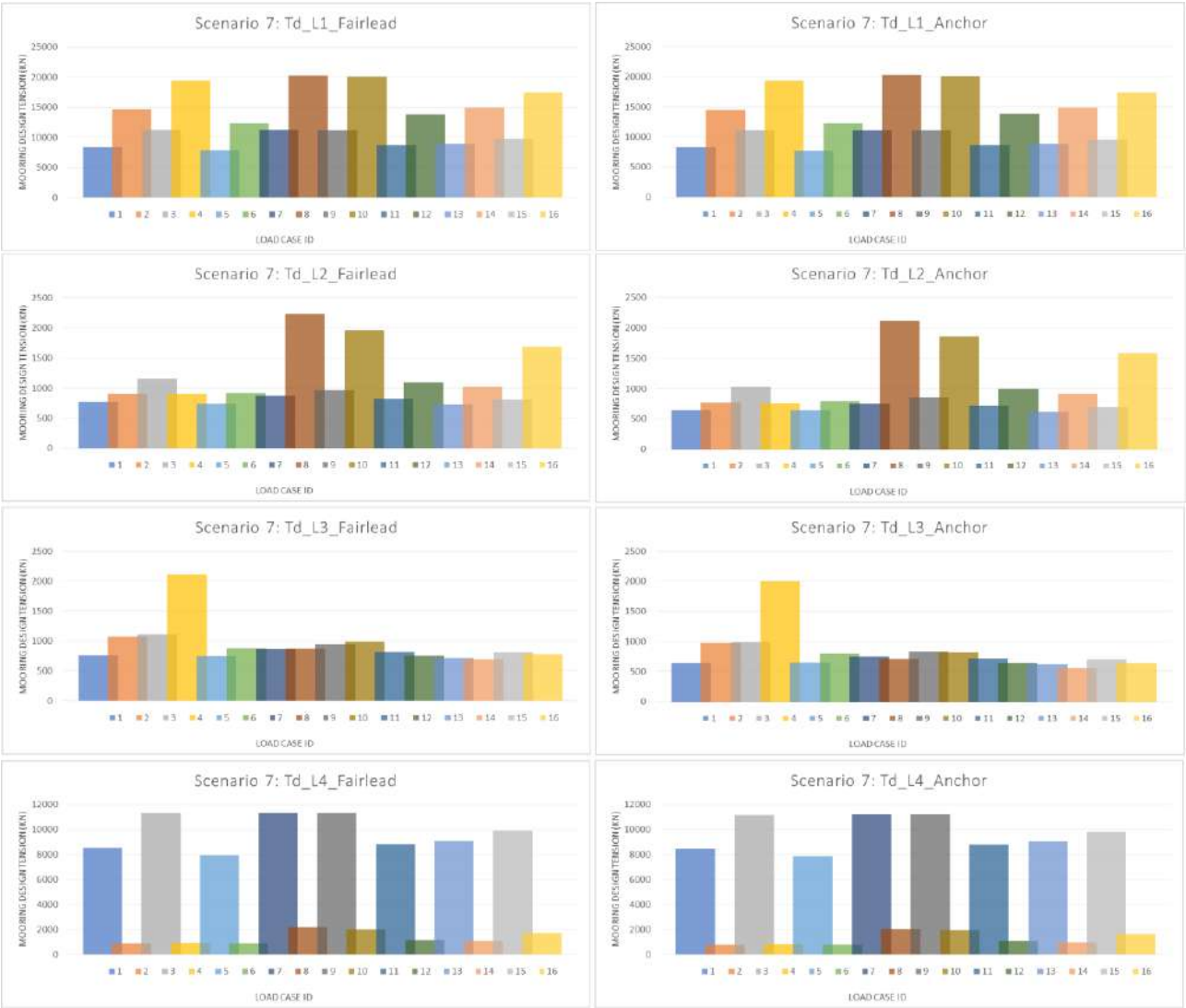
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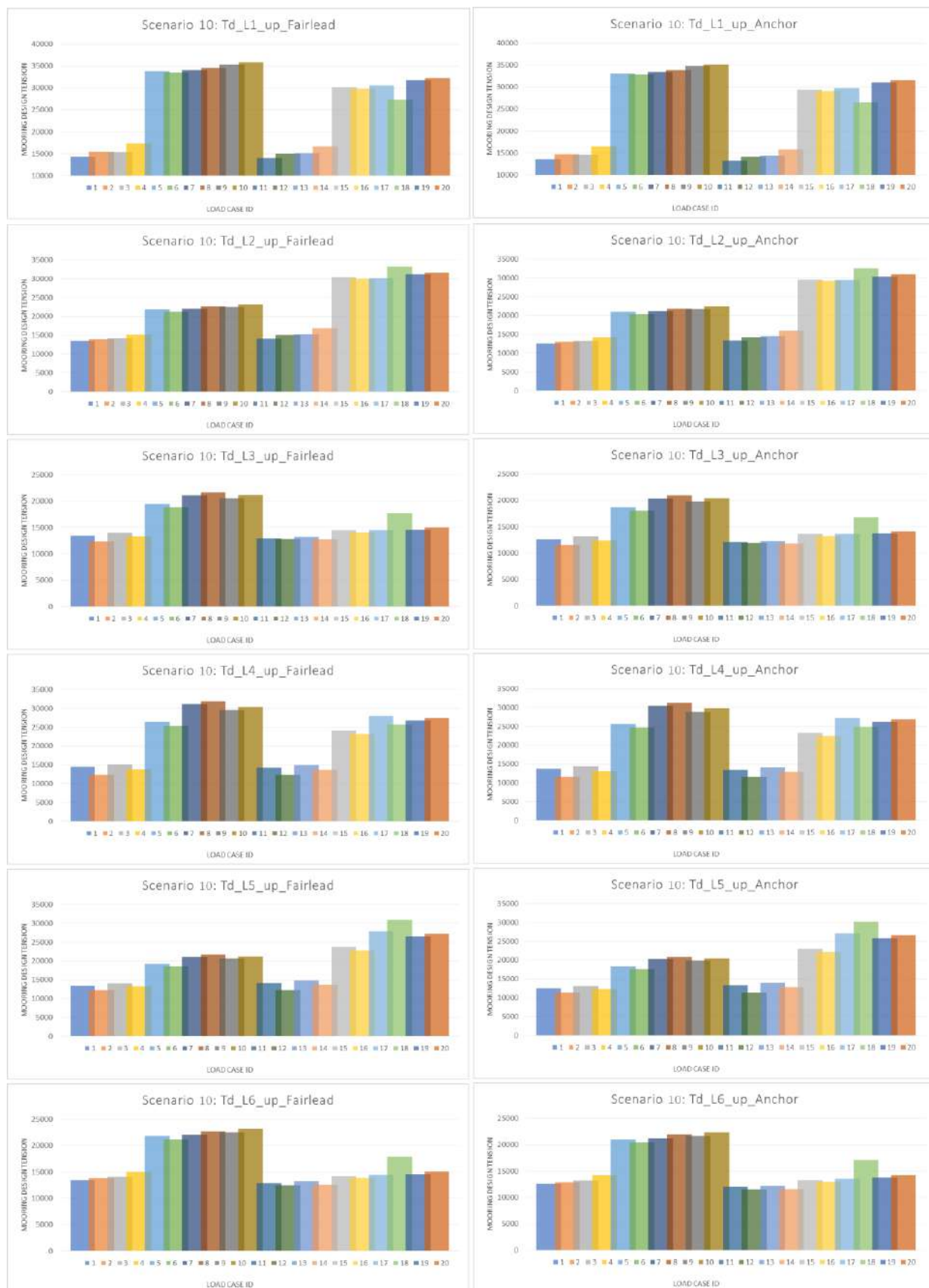
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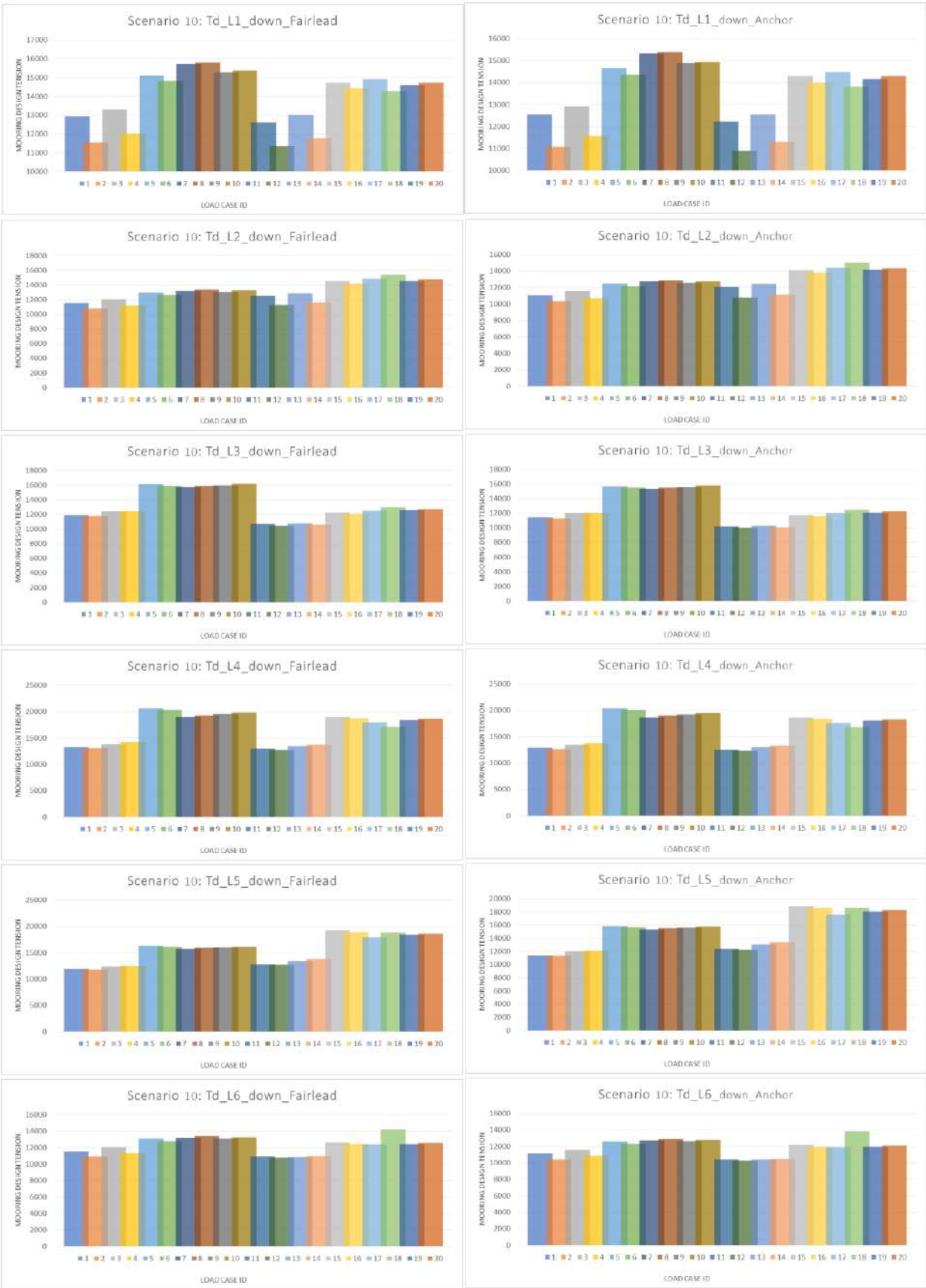


Scenario 7

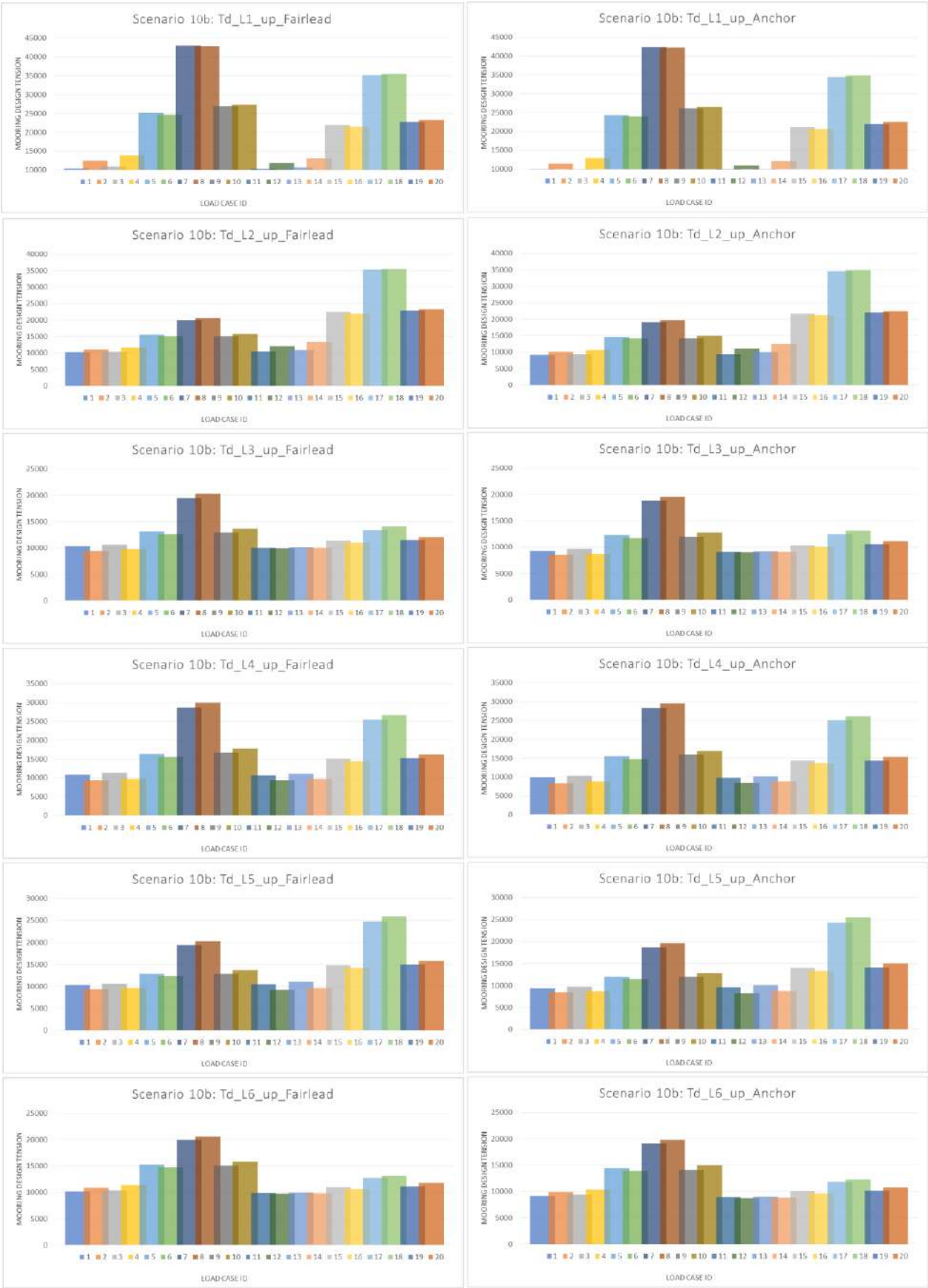


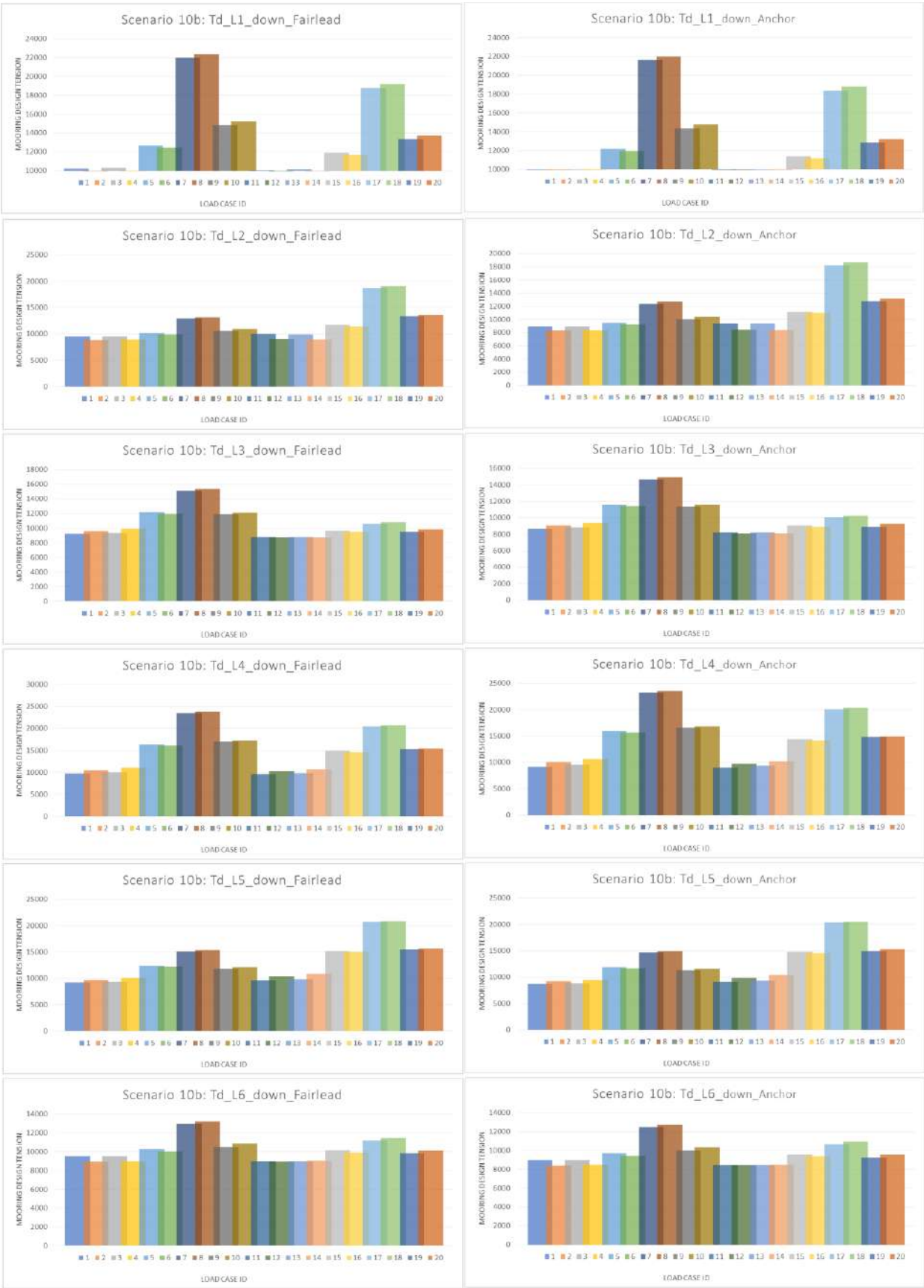
Scenario 10



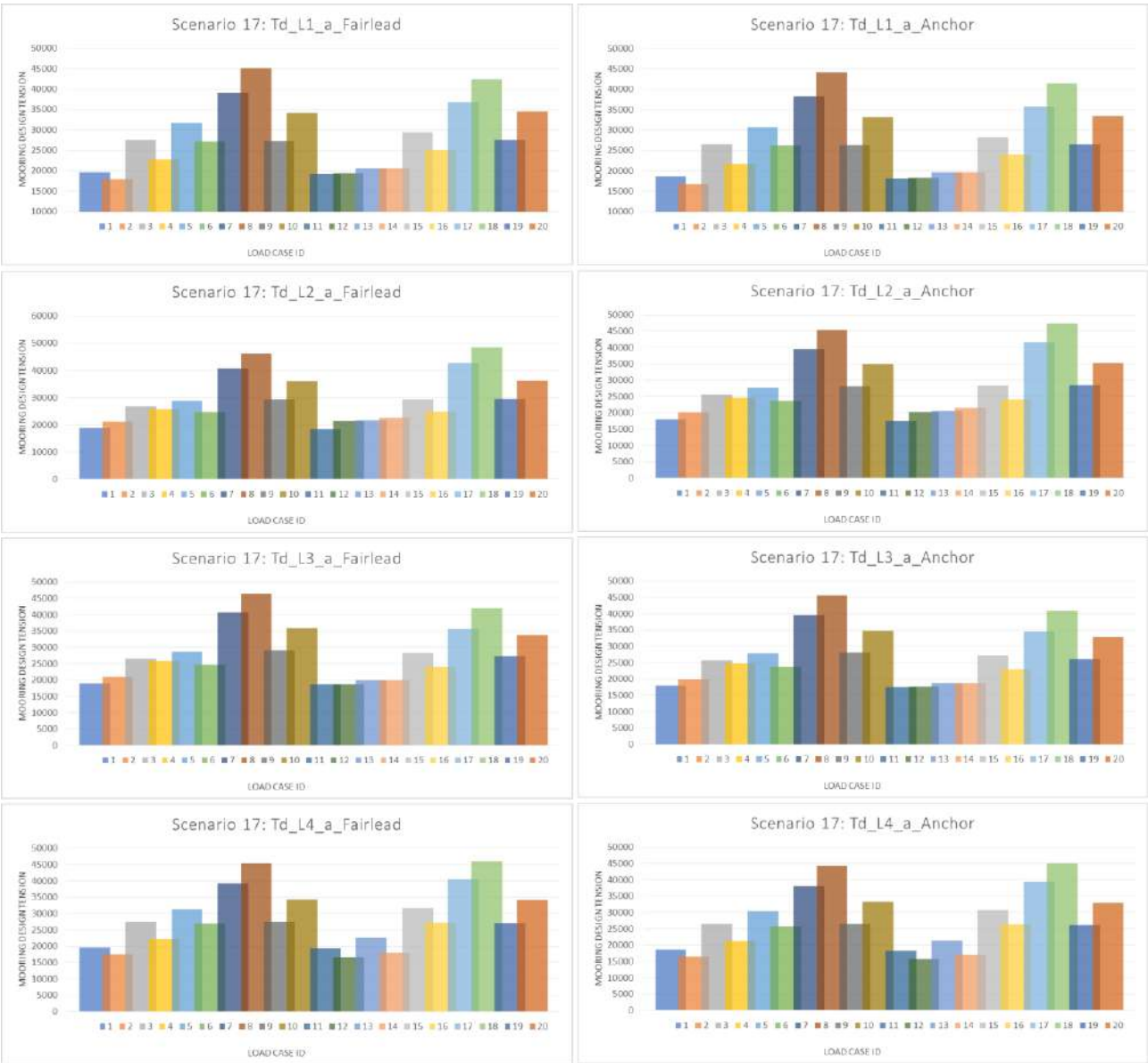


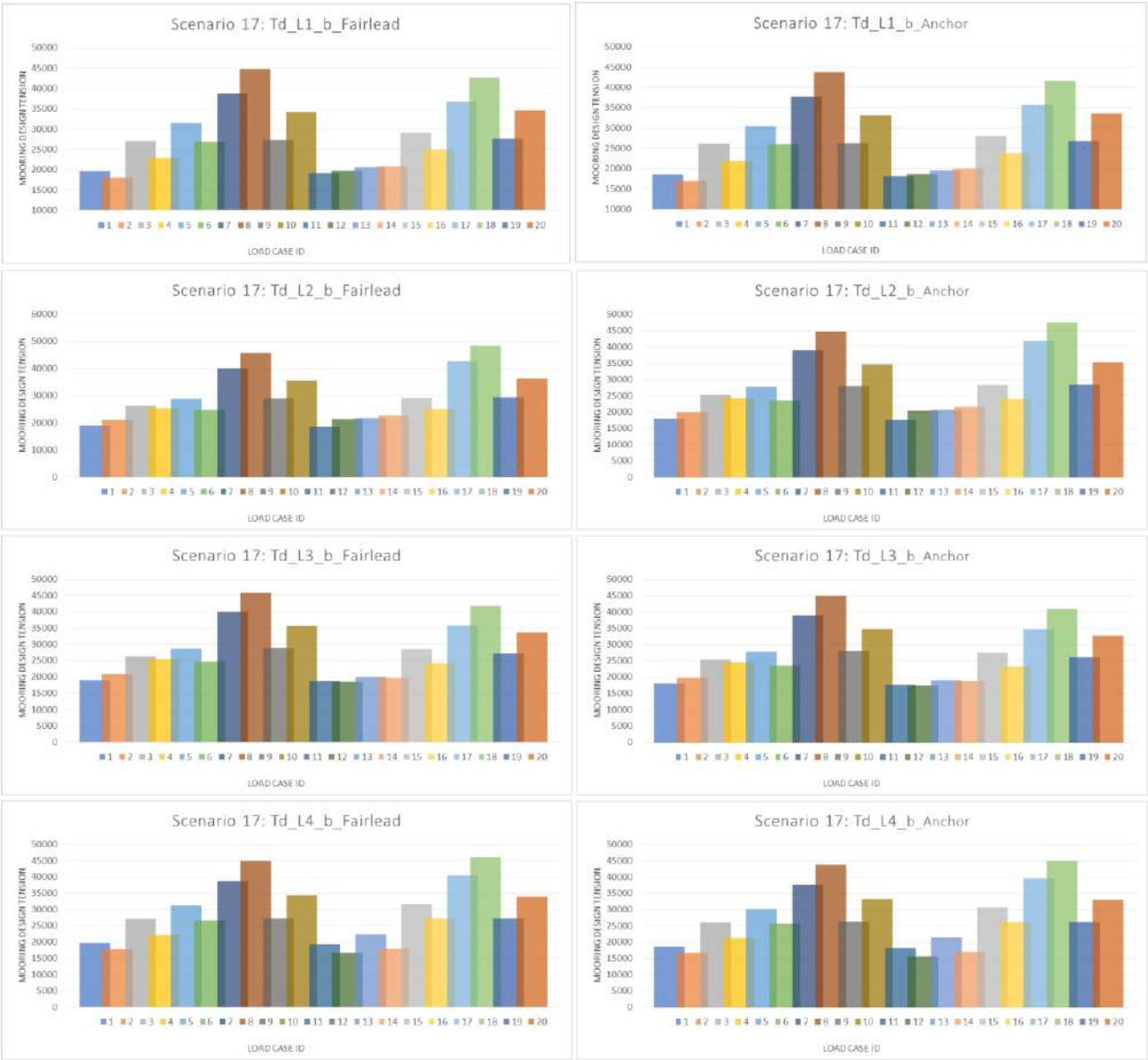
Scenario 10b





Scenario 17





Scenario 20

