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MOORING SYSTEM FOR A SEMI-SUBMERSIBLE RIG IN ULTRA-DEEPWATER AND UNDER SEVERE CURRENTS

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Abstract

In the nearby future, deepwater and ultra-deepwater Exploration and Production activities will represent most of the Oil and Gas Industry operations in Brazil, West Africa and Gulf of Mexico. This paper consist of the mooring analysis in water depth of 2,000m, 2,500m and 3,000m on Basins of North and Northeast of Brazil with severe current, wind and wave conditions using a standard anchor handling tug and supply vessel (AHTS). Alternatives in mooring systems are evaluated based on the rig preferable mooring spread, fairlead angle limitation and proposed mooring components. Due to increase of water depth in Mobile Offshore Drilling Unit (MODU) mooring, the development of different types of mooring system configuration in order to meet mooring line safety factor and rig offset requirements is becoming crucial. The case study presented in this paper considered different types of mooring systems: Wire-Chain system (catenary) and Chain-Polyester-Chain system (taut-leg). The mooring analysis was done with the rig Noble Clyde Boudreaux (NCB) that has capacity to be moored at 3,048m of water depth and to drill until 10,668m depth. The results show that it is possible to moor a semi-submersible rig in ultra-deepwater fields under extreme environmental conditions, considering the premises and methodology described in this paper.

1. Introduction

During the 11th Bidding Round of Blocks for Exploration and Production in Brazil, where 166 offshore blocks were offered, 40 blocks were acquired by Total, Queiroz Galvão, Petrobrás, BP, BG, Chevron, ExxonMobil and other Oil & Gas companies. The offshore industry is preparing for ultra-deepwater drilling and production in water depths exceeding 2,000 meters, especially in Basins of North and Northeast of Brazil.

This paper analyzes the feasibility to install a mooring system with different types of mooring components and mooring configuration in a deepwater and ultra-deepwater (2000m, 2500m and 3000m) under severe environmental conditions. Different mooring system configurations bring to the Oil & Gas industry new concepts in mooring system response. For example, using the heavy combination of wire rope and chain for conventional mooring lines or using lighter materials such as polyester and HMPE rope for taut leg mooring systems provides solutions with different performance. Wire-chain systems usually allow the MODU a large offset, which reduces the mooring system restoring force. On the other hand, lighter components, such as polyester ropes, reduce the MODU offset and increase the mooring system restoring force due to the polyester rope natural characteristic.

Despite the trend to use dynamic positioned platforms for exploratory campaigns in ultra-deepwater, moored semi-submersibles are still economical solutions for long period activities. The mooring industry should keep developing technologies for such complex scenarios ensuring safe operations and acceptable costs within the operator's project requirements.

2. Design Requirements

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The proposed mooring system for Noble Clyde Boudreaux at the three different locations was designed to meet the following design criteria.

The minimum mooring line break strength safety factor for intact and damaged conditions shall meet the API RP 2SK 3rd edition. The API RP 2SK requirements are presented in the Table 1 for intact and damaged conditions. The limiting for the maximum vessel offset was obtained based on a linear approximation by the API RP 16Q requirements for lower flex joints rotations. The vessel offset limits for NCB are presented in the Table 2 for drilling, non-drilling and survival conditions.

Mooring line tensions in a zero (0) environment shall not exceed the stall capacity of their respective winches which is 226t (500kips) in either operating or extreme safe conditions. The Mooring analyses were performed considering three (03) mooring line pre-tensions of 136t (300kips), 150t (331kips) and 172t (380kips) in order to achieve the mooring line safety factor and the rig offset. Section 4.4 illustrates the mooring line tension used for each case.

The mooring lines shall have a minimum angle at the fairlead, large enough to prevent contact with the rig's bolsters in a zero (0) environment with the 45º- 45º for eight (08) mooring lines and 30º- 30º for twelve (12) mooring lines spread as presented in the Sections 4.1 and 4.4. The fairlead angle must be also equal to or less than 74º (relative to waterline) for all mooring lines.

Table 1. Mooring Line Dynamic Safety Factor Criteria – API RP 2SK

Mooring Line Break Strength Dynamic Safety Factor	
Intact	**Damage**
1.67	1.25

Table 2. Vessel Offset Criteria

Design Criteria for Drilling Riser Analysis			**Maximum Vessels Offset (% Water Depth)**	
Condition	**Drilling**	**Non-Drilling and Survival**	**Intact**	**Damaged**
Extreme Lower Flexjoint Rotations	± 4º maximum	± 9º maximum	6.99	15.83

3. Methodology

Mooring analyses were carried out for Noble Clyde Boudreaux using the software GMoor32 version 9.5.2.3 using frequency-domain analysis method.

Mooring line configurations were modeled to accurately simulate each mooring component's dynamic characteristics, including length, weight, diameter, stiffness, friction, drag and added mass coefficients.

Omnidirectional and collinear wind, waves and current were modeled using the metocean data listed in Section 4.3 of this paper. The environment condition was imposed on the rig and its moorings from headings encompassing the full 360° in 5° increments.

Quasi-static and dynamic analyses were performed. Dynamic line tensions were analyzed due to the first order motions using static and dynamic line tensions. Low frequency analyses were performed considering the slowly varying response to wave drift and wind gust forces. A transient analysis was not performed.

Intact and damaged (i.e., single mooring line broken) conditions were analyzed for each heading. This was done such that all eight (08) and twelve (12) of the mooring lines were broken sequentially for each environmental heading, but at no time were two (2) lines broken simultaneously.

4. Input Data

Inputs and assumptions used to develop the presented study are based on the following sections:

- Noble Clyde Boudreaux general informations.
- Site Information and soil data.
- Environmental conditions.

- Mooring Line Configurations.

The anchor will not be defined in the present paper. The herein objective is to determine the maximum anchor tension as well as the maximum anchor uplift angle, subsequently the anchor can be determined in the next phase.

4.1 Noble Clyde Boudreaux General Informations

Figure 1 provides an image and general information of the Noble Clyde Boudreaux. She is a semi-submersible quadrangular drilling rig, composed by sixteen (16) mooring lines, where eight (8) mooring lines can be used for standard mooring configuration and the remain eight (8) for storm conditions. The NCB current mooring system configuration is composed by studlink chain and wire rope, more information regarding the specifications for the mooring components can be found in the Section 4.4. When eight (08) mooring lines (#2, #3, #6, #7, #10, #11, #14 and #15) are deployed, the NCB preferable mooring spread is 45^0-45^0, in the other hand when twelve (12) mooring lines (#1, #2, #3, #5, #6, #7, #9, #10, #11, #13, #14 and #15) are used the mooring spread was change to 30^0-30^0.

In this present study the mooring analyses were performed considering only the operational draft, as per rig owner recommendation. The hydrostatic data for operational draft are presented in the Table 3.

NCB Information	
Length Overall	96.99 m
Breadth	75.59 m
Depth	30.48 m
Draft (1)	20.2 m
Maximum Mooring Water Depth	3,048 m

Figure 1 – NCB Main Characteristics

Table 3- NCB Hydrostatic Data

NCB Hydrostatic Data			
Longitudinal Center of Gravity	-1.22 m	GMT	2.09 m
Transversal Center of Gravity	0	GML	2.88 m
Vertical Center of Gravity	20.42 m	Mass Weight	433,949,939 N
Longitudinal Center of Buouncy	-1.22 m	Displaced Volume	43,183 m^3
Transverse Center of Buouncy	0	Displaced Mass	44,266,582 Kg
Vertical Center of Buouncy	7.33 m	Waterplane Area	952 m^2

As per item (1) presented in the Figure 1 and in the Table 3 it is important to notice that the Hydrodynamic model was generated using HydroD software that uses a global right-handed Cartesian coordinate system. The hydrodynamic model was generated in the global coordinate system described below:

- The positive x-axis points forward with the longitudinal origin at midship.
- The positive y-axis points to port with the transverse origin at centerline.
- The positive z-axis points upward with the vertical origin at the still water line.

The direction of the environments is given in the global coordinate system as follows:

- Bow-on environment = 180º
- Beam-on environment = 90º
- Stern-on environment = 0º

The results are also given about the global coordinate origin (i.e., midship, centerline, water line).

- In reference to input origin

4.2 Site Information and Soil Data

Three water depths mentioned before were considered in the mooring design. The analyses were performed assuming the field layout with no slope and no subsea infrastructure, archaeological sites and biologically sensitive (corals) on seafloors regions and considering a nonspecific soil data. Figures 2 and 3 shows the mooring plan for NCB at the three (03) water depths. Note that horizontal distance changes in each water depth.

4.3 Environmental Conditions

Wind, wave and current were modeled as recommended in API RP 2SK 3rd Edition, using two environmental conditions of operational and extreme condition. The environmental conditions were obtained based on InterMoor do Brasil experience and the details of the metocean design data used for the analyses are provided in the Table 4.

In addition to the operational and extreme design environmental condition, another environmental condition was evaluated. A severe environmental condition that represents the extreme values for wind and current added to a severe sea wave (higher values of sea wave height-Hs, peak period-Tp and peakedness parameter-ɣ) was also analyzed.

Considering the severe environmental condition, a new sensitivity analysis was performed in order to verify the mooring response due to different values of peak period. In this scenario, the extreme values for wind and current associated with a severe sea wave with constant peakedness parameter of 3.0 was maintained as a constant and the Tp was varied with 7s, 10s, 12.1s, 15.5s and 18.0s. All environmental conditions were analyzed at operational draft.

Since the predominate wind and current directions are from the northeasterly-southeasterly quadrant, the NCB was positioned in with 45º of bow heading.

Table 4. Metocean Design Data

Environmental Component	Operational Condition	Extreme Condition	Severe Condition
Wind:			
Wind spectrum	BOMOSHU[1]	BOMOSHU[1]	
Speed, Vw(1hour mean at 10m)	15.0 m/s (29.13 knots)	25.0 m/s (48.54 knots)	
Full Sea Waves:			
Wave Spectrum	JONSWAP	JONSWAP	JONSWAP
Significant Wave High, Hs	5.5 m (18.04 ft)	5.5 m (18.04 ft)	7.84 m (25.72 ft)
Peak Period, Tp	12.1 sec	12.1 sec	15.5 sec
Peakedness Parameter, ϒ	2	2	3
Current:			
Surface Speed, Vc	1.69 m/s (3.28 knots)	2.20 m/s (4.27 knots)	

Notes: 1) Brazil Offshore Meteorological and Oceanographic Study

4.4. Mooring Configurations

Several mooring configurations have been considered in this paper. The first mooring system to be investigated was the heavy combination of conventional (wire-chain) system, which consist of mooring the Noble Clyde Boudreaux with eight (08) and twelve (12) mooring lines at all studied water depths using her current mooring components of 95mm wire rope (fairlead component) and 84mm studlink chain (ground component), presented in the Table 5.

Table 5. Chain-Wire Rope Mooring Components Proprieties

	Wet Weight (kg/m)	Elasticity - EA (mT)	Break Strength (mT)
95 mm Wire Rope	36	47,037	810
84 mm R5 Rig Chain	130	56,444	828

The mooring system was balanced with 150 tons of pre-tension on fairlead. Due to the increase in the water depth, the fairlead component was adjusted in order to achieve the design horizontal distance. The wire-chain mooring systems with eight and twelve mooring lines are described below in the Tables 6 and 7, respectively.

Table 6. Chain-Wire Rope Mooring Configuration with 8 mooring lines

Case	Water Depth	Horizontal Distance	Rig Heading	Tension at the Fairlead	Wire Rope		Studlink Chain	
					Type	Lenght	Type	Lenght
1	2,000 m	2,700 m	45.00º	150t	95 mm Wire Rope	~ 2,373 m	84 mm R5	1,300 m
2	2,500 m	3,000 m				~ 3.026 m		
3	3,000 m	3,300 m				~ 3,700 m		

Table 7. Chain-Wire Rope Mooring Configuration with 12 mooring lines

Case	Water Depth	Horizontal Distance	Rig Heading	Tension at the Fairlead	Wire Rope		Studlink Chain	
					Type	Lenght	Type	Lenght
4	2,000 m	2,700 m	45.00º	150t	95 mm Wire Rope	~ 2,370 m	84 mm R5	1,300 m
5	2,500 m	3,000 m				~3,022 m		
6	3,000 m	3,300 m				~ 3,700 m		

The second mooring system to be investigated was the taut-leg (chain-polyester) system, which consists of mooring the Noble Clyde Boudreaux with eight (08) and twelve (12) mooring lines at all studied water depths. Analyses with different types of chain besides polyester rope were performed and the best mooring line configuration found was composed by 84mm studlink chain (fairlead component), 144mm polyester rope and 84mm studlink chain (ground component). Due to the complex nature of polyester rope stiffness, it was necessary to perform the mooring analysis using more than one (1) stiffness value in order to capture both the maximum mooring line tensions and maximum vessel offsets. For the purpose of this analysis the drift and storm stiffness values listed below in the Table 8 were used to evaluate the maximum vessel offsets and maximum mooring line tensions respectively.

- Drift stiffness = 10 x polyester break strength defined as Low EA Poly.
- Storm stiffness = 34 x polyester break strength defined as High EA Poly.

Table 8. Chain-Polyester-Chain Mooring Components Proprieties

	Wet Weight (kg/m)	**Elasticity - EA (mT)**	**Break Strength (mT)**
144 mm Polyester Rope	4	Low - 7,100 High - 24,140	710
84 mm R5 Rig Chain	130	56,444	828

Depending on each case, the mooring system was balanced with 136 tons, 150 tons and 172 tons of pre-tension on fairlead. Due to the increase in the water depth, the fairlead component was adjusted in order to achieve the horizontal distance at the proposed fairlead tension. The chain-polyester mooring systems with eight and twelve mooring lines are described below in the Tables 9 and 10, respectively.

Table 9. Chain-Polyester Rope-Chain Mooring Configuration with 8 mooring lines

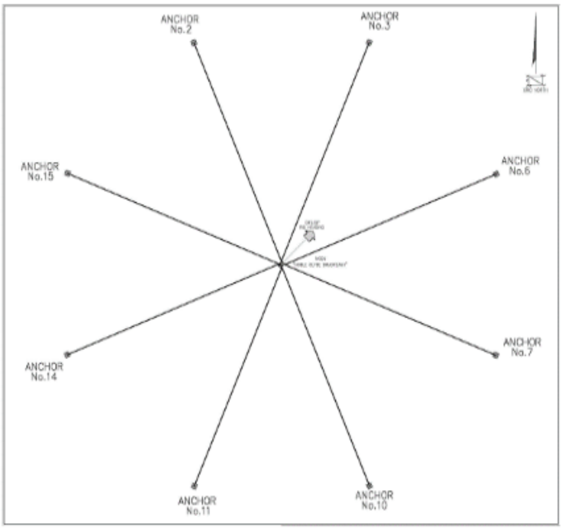
Case	Water Depth	Horizontal Distance	Rig Heading	Tension at the Fairlead	Studlink Chain		Polyester Rope		Studlink Chain	
					Type	Lenght	Type	Lenght	Type	Lenght
7	2,000 m	2,600 m	45.00º	136t	84 mm R5	~ 481 m	144 mm Poly	2,500 m	84 mm R5	300 m
8	2,500 m	2,900 m		150t		~ 652 m		3,000 m		
9	3,000 m	3,300 m		172t		~ 874 m		3,500 m		

Table 10. Chain-Polyester Rope-Chain Mooring Configuration with 12 mooring lines

Case	Water Depth	Horizontal Distance	Rig Heading	Tension at the Fairlead	Studlink Chain		Polyester Rope		Studlink Chain	
					Type	Lenght	Type	Lenght	Type	Lenght
10	2,000 m	2,600 m	45.00º	136t	84 mm R5	~ 478 m	144 mm Poly	2,500 m	84 mm R5	300 m
11	2,500 m	2,900 m		172t		~ 500 m		3,000 m		
12	3,000 m	3,300 m		172t		~ 642 m		3,500 m		

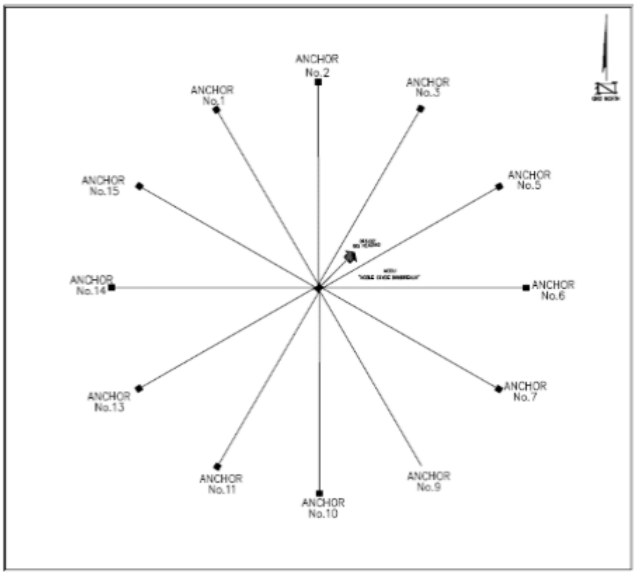
Note that the tension at the fairlead in the case 11 (twelve mooring lines deployed) was increased compared to the case 8 in order to achieve both the mooring line safety factor and vessel offset for the operational and extreme environmental condition.

The mooring plans for NCB with 8 and 12 mooring lines with taut-leg system are presented in figures 2 and 3 respectively.



Leg No	Leg Heading	Water Depth of 2,000m		Water Depth of 2,500m		Water Depth of 3,000m	
		Fairlead to Anchor Horiz. Distance	Water Depth at Anchor	Fairlead to Anchor Horiz. Distance	Water Depth at Anchor	Fairlead to Anchor Horiz. Distance	Water Depth at Anchor
2	337.5°	2,600 m	2,000 m	2,900 m	2,500 m	3,300 m	3,000 m
3	22.5°						
6	67.5°						
7	112.5°						
10	157.5°						
11	202.5°						
14	247.5°						
15	292.5°						

Figure 2. Mooring Plan with 8 lines



Leg No	Leg Heading	Water Depth of 2,000m		Water Depth of 2,500m		Water Depth of 3,000m	
		Fairlead to Anchor Horiz. Distance	Water Depth at Anchor	Fairlead to Anchor Horiz. Distance	Water Depth at Anchor	Fairlead to Anchor Horiz. Distance	Water Depth at Anchor
1	330°	2,600 m	2,000 m	2,900 m	2,500 m	3,300 m	3,000 m
2	0°						
3	30°						
5	60°						
6	90°						
7	120°						
9	150°						
10	180°						
11	210°						
13	240°						
14	270°						
15	300°						

Figure 3. Mooring Plan with 12 lines

5. Results

The results of the mooring analyses considering the NCB moored with eight (08) mooring lines with operational environmental condition, the wire-chain system achieve the mooring lines safety factor for all water depths, however the vessel offset obtained in the analyses were larger than the limits considered in the Table 2. Moreover, when the extreme environmental conditions were analyzed, the rig was not able to achieve the recommended minimum mooring lines safety factor. In order to find one mooring configuration that will achieve the minimum mooring line safety factor using only the current rig components, one mooring lines were added per rig corner, totaling in twelve mooring lines.

The results for NCB moored with 12 mooring lines composed by wire-chain mooring system with operational and extreme environmental condition achieve the mooring lines safety factor for all water depths; however the vessel offset obtained in the analyses were larger than the limits considered in the Table 2. Thereat the mooring analyses results will not be presented in this paper.

For the taut-leg mooring system the first analysis was performed considering the NCB moored with eight mooring lines at operational condition. The mooring line safety factors obtained in this analysis are within the criteria as per Section 2 as well as the vessel offset except for the 3,000m water depth. Table 11 summarizes the results. When the extreme environmental condition was imposed on the rig, the mooring line could not achieve the minimum safety factor as well as the vessel offset found was larger than the limits provided in the Section 2.

Table 11. Mooring Analysis Results Summary for Mooring Configuration with 8 mooring lines

Case	Environmental Condition	Water Depth	Maximum Vessels Offset (% Water Depth)		Maximum Uplift Angle at anchor (º)		Maximum Tension at Anchor (mT)	
			Intact	Damage	Intact	Damage	Intact	Damage
7	Operational Condition	2,000	5.90	10.50	28.9	31.4	277	425
8	Operational Condition	2,500	6.83	11.49	31.4	33.9	274	422

In order to find a solution for the extreme environmental condition, the same methodology used for wire-chain system was implemented in the taut-leg mooring system. Consequently, when twelve mooring lines were deployed, the NCB could sustain the operational and extreme environmental condition which means that both the minimum mooring line safety factor and vessel offset are within the API RP 2SK recommendation as well as a linear approximation performed according to API RP 16Q. The results for the NCB composed by eight and twelve mooring lines with operational environmental condition are presented in Figures 4, 5 and 6 and for the extreme environmental condition are presented in the Figures 7, 8 and 9. Table 12 shows the mooring analysis results summary for the twelve mooring lines.

Table 12. Mooring Analysis Results Summary for Mooring Configuration with 12 mooring lines

Case	Environmental Condition	Water Depth	Maximum Vessels Offset (% Water Depth)		Maximum Uplift Angle at anchor (º)		Maximum Tension at Anchor (mT)	
			Intact	Damage	Intact	Damage	Intact	Damage
10	Operational Condition	2,000 m	4.31	6.21	26.3	29.1	204	286
11	Operational Condition	2,500 m	4.87	6.83	29.0	32.0	198	281
12	Operational Condition	3,000 m	5.70	7.80	29.1	32.6	188	275
10	Extreme Condition	2,000 m	6.91	9.66	30.2	31.7	339	462
11	Extreme Condition	2,500 m	5.43	7.99	33.9	35.2	344	464
12	Extreme Condition	3,000 m	6.38	9.04	34.8	36.2	343	468

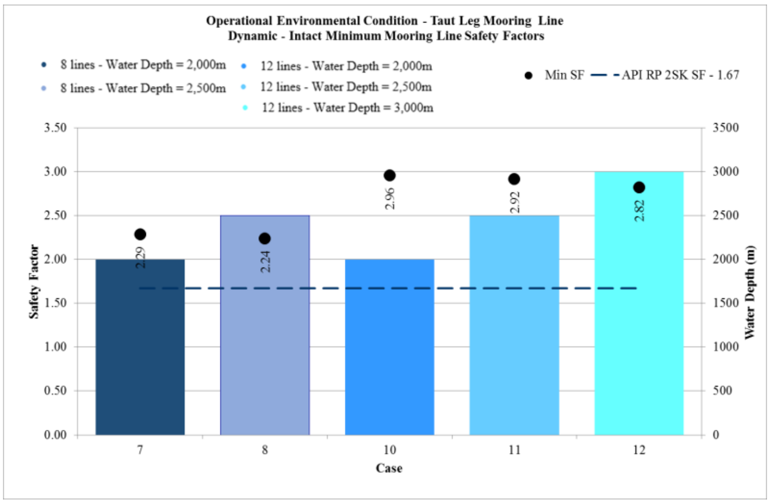


Figure 4. Minimum Mooring Line Intact Safety Factor – Operational Environmental Condition

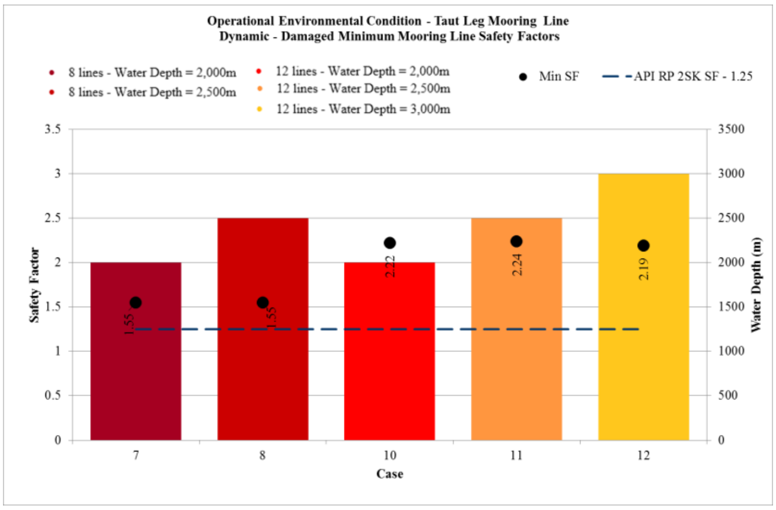


Figure 5. Minimum Mooring Line Damaged Safety Factor – Operational Environmental Condition

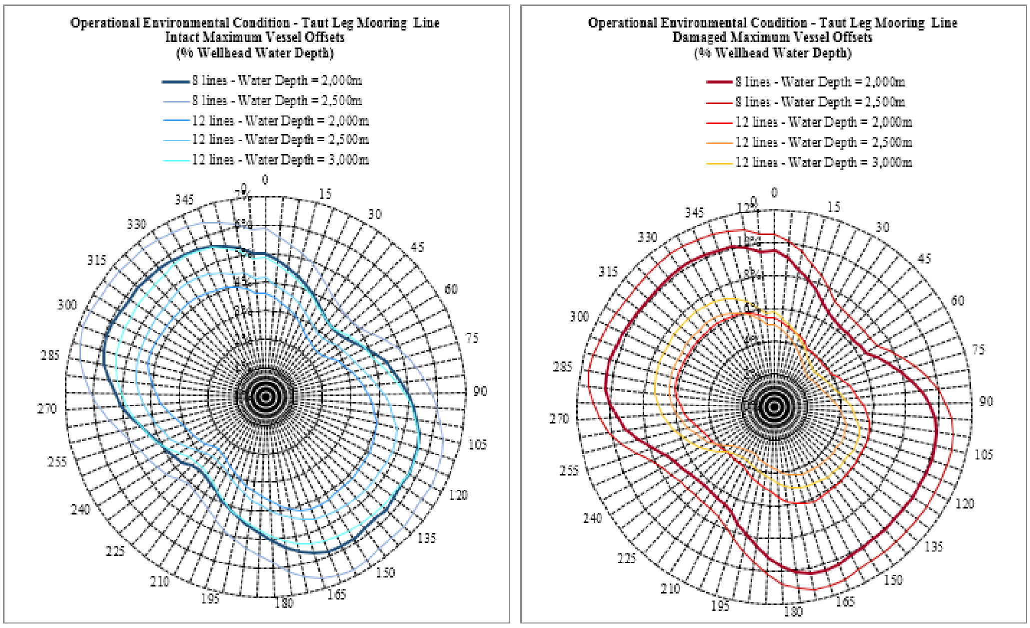


Figure 6. Maximum Vessel Offsets – Operational Environmental Condition

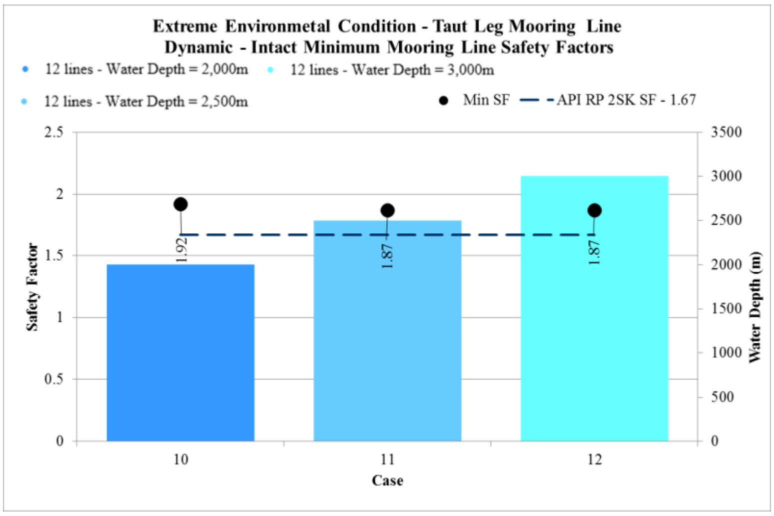


Figure 7. Minimum Mooring Line Intact Safety Factor – Extreme Environmental Condition

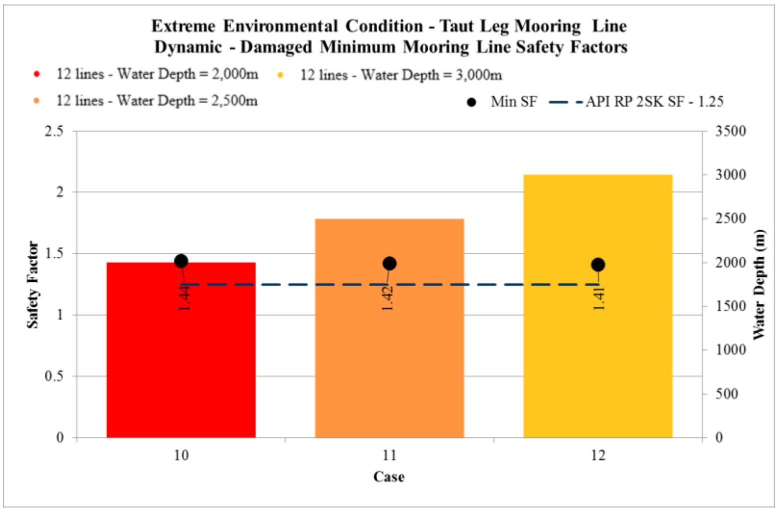


Figure 8. Minimum Mooring Line Damaged Safety Factor – Extreme Environmental Condition

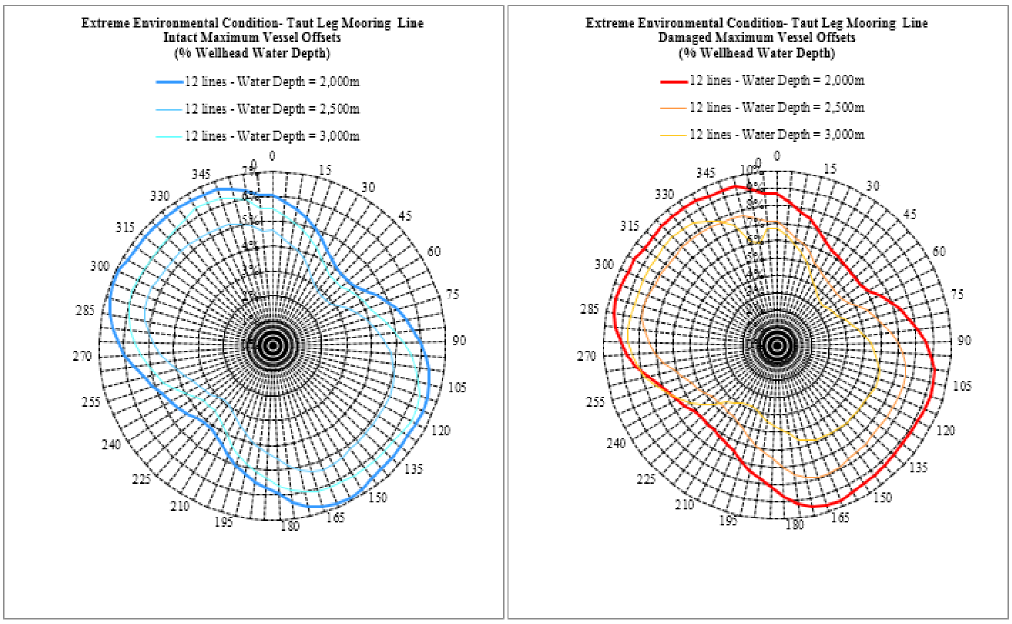


Figure 9. Maximum Vessel Offsets – Extreme Environmental Condition

A variation in the Tp for a severe environmental condition was performed considering the NCB with 12 mooring lines deployed at 2,000m of water depth and the results were satisfactory. The rig can be moored under this environmental condition, the Table 13 shows the mooring analysis results summary.

Table 13. Mooring Analysis Results Summary with 12 mooring lines under severe environmental condition

Case	**Environmental Condition**	**Water Depth**	**Min. Mooring Line Break Strength Dynamic Safety Factor**		**Maximum Vessels Offset (% Water Depth)**		**Max. Uplift Angle at anchor (°)**		**Maximum Tension at Anchor (mT)**	
			Intact	**Damage**	**Intact**	**Damage**	**Intact**	**Damage**	**Intact**	**Damage**
8	Severe	2,000 m	1.85	1.42	6.05	8.67	30.5	31.9	344	463

6. Conclusions

The results described above shows that a semi-submersible MODU can be moored in deepwater and ultra-deepwater under extreme environmental condition as per the design requirement, premises and analysis methodology.

The mooring analyses were performed considering a metocean data conservative based of North and Northeast of Brazil regions. The vessel offsets listed may be very conservative, as they were developed assuming an omnidirectional collinear environment imposed on the rig and its mooring system through the full 360°. Consequently, they do not account for reductions in offset associated with the environmental directionality. If necessary, the operators can provided more accurate metocean data and the offset values can be revaluate.

The vessel offset criteria presented in the Section 2 of this paper, was estimated based on linear approximation of the extreme lower flex joint rotations provided by API RP 16Q. However, other components in the drilling riser string can be the limiting such as the riser stresses, connectors capacities and telescopic joints stroke. The operators shall provide the drilling riser operability limitations in order to perform the mooring analysis considering the accurate vessel offset criteria. It is also required to evaluate the mooring system considering the transient analysis to ensure compliance with API RP 2SK.

One of the reasons that was necessary to increase 4 mooring lines in the system when the safety factor and or the vessel offset was not achieved is the exposed water plane area when the environmental condition goes to northwest. When the mooring lines #1, #5, #9 and #13 were added to the mooring pattern the NCB could restore the forces, reducing the rig offset and the mooring line tension.

As the anchor was not defined in this paper; it can be selected based on the drilling location (soil data information) and maximum anchor tension (intact and damaged) and uplift found in the analyses. For this particular case studied in this paper, those values can be obtained from the Section 5. With the anchor selected, the safety factor can be calculated and the minimum safety factor shall be achieved according to API RP 2SK criteria.

Also, it is important to mention that as soon as early information are provided as field layout, soil and metocean data as well as the vessel information, the mooring analysis can be performed in advance considering accurate limits.

This paper proves that, despite the trend to use dynamic positioned platforms for exploratory campaigns in ultra-deepwater, a semisubmersible rig can be used in this scenario and under extreme environmental condition.

7. References

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Software GMoor 32 V9.520.3.

Software Sesam™ HydroD V2.1-06.