International Journal of Marine Engineering Innovation and Research, Vol. 8(4), Dec. 2023. 802-809
(pISSN: 2541-5972, eISSN: 2548-1479)

Reliability Analysis on the Effect of Subsea Buoy to the Tension of Spread Mooring System

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(Received: 22 December 2023 / Revised: 23 December 2023 /Accepted: 27 December 2023)

Abstract— **A lot of research has been carried out regarding variations in mooring systems, one of which is the addition of buoys to the mooring system. In analyzing variations in mooring system designs, what needs to be considered is the reliability of the mooring lines. Therefore, in this research will analyze reliability on the effect of subsea buoy to the tension of mooring line with a variation position of subsea buoy. The variations on the position of one subsea buoy is arranged at the distance of the anchor 605 m, 577.5 m, 550 m, 522.5 and two subsea buoys at the distance from the anchor 605 m and 467.5 m. The analysis was performed for stand alone and offloading conditions with wave directions of 0 °, 45 °, 90 °, 135 °, 180 °. In this study to find the reliability of mooring lines, the author uses the Mean Value First Order Second Moment (MVFOSM) method. The results from this study, the probability of failure in the offloading condition without subsea buoy is 4.897E-17 and with subsea buoy (522.5 m) is 4.018E-17. Probability of failure in the stand alone condition without subsea buoy is 2.763E-16 and with subsea buoy (522.5 m) is 1.881E-16. From the probability of failure, the reliability of mooring lines in the offloading condition and stand alone condition without subsea buoy and with subsea buoy (522.5 m) is 1.00. The reliability calculation determined by DNV-OS E301, the results obtained meet the specified reliability criteria.**

Keywords— Reliability, MVFOSM, FSO, spread mooring, subsea buoy, tension.

I. INTRODUCTION

Floating Offshore Storage (FSO) is a ship-shaped floating structure used to store oil or gas offshore. The oil or gas from the FSO channeled through a floating hose to a tanker or barge to be brought ashore. FSO structures experience movement caused by environmental loads, such as wind, waves and currents. Therefore, a mooring system is needed to anchor the FSO structure. The mooring system aims to limit ship movement and keep the FSO structure in position. One of the most common mooring systems used for mooring FSOs is the spread mooring system. In a typical spread mooring system, groups of mooring lines terminate at the ship's corners to ensure a stable ship course. Spread mooring systems can be designed to hold vessels in place regardless of the direction of the environment. The mooring line is moored on the seabed and connected to a floating substructure, and has a small flexural stiffness so that external loads are supported by tension in the mooring line. External loads include the weight of the substructure, hydrodynamic tensile forces in the normal, tangential and bi-normal directions, and inertial forces [16].

Currently, a lot of research has been carried out regarding variations in mooring systems, one of which is the addition of buoys to the mooring system. The addition of a buoy to the mooring line is useful to avoid clashing between the mooring line and underwater equipment. Apart from that, there is research which states that adding buoys to the mooring line can reduce the tension that occurs on the mooring line. A numerical analysis has been carried out on a hybrid mooring system with clump weights and buoys which analyzes a new type of mooring line, hybrid mooring system with clump weights and buoys (HMSWB). In this study, analyze the effect of adding buoys, because the effect of adding clump weight has been analyzed previously [11]. From this research, the results showed that the addition of buoys can reduce the tension on mooring lines [17].

In analyzing variations in mooring system designs, what needs to be considered is the reliability of the mooring lines. Because the mooring lines in the mooring system will receive a combination of tensile, bending and fatigue loads [12]. In addition, due to the high operating costs of offshore facilities and their highly sensitive operation, assessing the reliability and risks of their design and operation, and especially the operation of mooring lines, becomes very important [7]. From research of the reliability of the FSO mooring line using the MVFOSM method explains that the reliability of the mooring line is influenced by pretension on the mooring line, MBL, and the environmental conditions the FSO is in as well as the load of the FSO [13]. A reliability analysis of the mooring system for fish cages in ALS conditions. shows that the failure of one mooring line significantly influences the possibility of failure of the remaining mooring lines [10].

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Furthermore, an analysis of the reliability of the mooring system on the SPM under extreme wave and current conditions has also been carried out, reliability analysis was carried out using the FORM method and this analysis shows that increasing or reducing the diameter of the mooring line will also affect the forces that occur on the mooring line [7]. Reliability analysis on SPM was also carried out using the MVFOSM method. From this research, it was concluded that the greater the tension that occurs on the mooring line, the lower the reliability of the mooring line [9].

In this research a reliability analysis will also be carried out, mooring line analysis is carried out with variations of one subsea buoy with four variations in the position and two subsea buoys. So that it can be seen the reliability the effect of tension on the spread mooring due to the addition of the subsea buoy. Previously analysis regarding the effect of subsea buoys to the tension of spread mooring systems has been carried out [15], So next the reliability analysis of the mooring line due to the effect of adding a subsea buoy to the spread mooring system will be carried out. Think of that the mooring line is a very important component in the mooring system and its reliability needs to be taken into account.

II. METHOD

A. FSO and Shuttle Tanker Model

The FSO model has a LOA of 244.6 meters and shuttle tanker has LOA 240.5 meters based on the characteristics described in Table 1 and Table 2. FSO and shuttle tanker in the free floating condition is first modeled and validated based on the *American Bureau of Shipping* (ABS.), which states that the difference of displacement modeling does not exceed 2% [1]. After validation, the simulation will analyze the hydrostatic and response amplitude operator (RAO). Two load conditions of FSO are analyzed: full and ballast conditions. The suttle tanker was analyzed in full load condition.

FSO is also modeled in a moored condition. There are two conditions: stand alone and offloading. The main object in this research is the mooring line with subsea buoy, modeled with the properties shown in Table 3. Table 4 displays environmental load consisting of wind, current, and waves varied from eight directions.

TABLE 1.
FSO DATA

Length Overall (m)	244.60
Length Between Perpendicular (m)	233.00
Breadth Moulded (m)	42.20
Depth Moulded (m)	22.20
Draft in full load condition (m)	14.90
Draft in ballast condition (m)	7.00
Displacement in full load condition (ton)	128,588.60
Displacement in ballast condition (ton)	58,796.11

TABLE 2.
SHUTTLE TANKER DATA

Length Overall (m)	240.50
Length Between Perpendicular (m)	230.00
Breadth Moulded (m)	42.00
Depth Moulded (m)	21.20
Draft (m)	14.85
Displacement (ton)	118,643.87

TABLE 3.
MOORING SYSTEM DATA

Subsea Buoy		Mooring Chain	
Weight (kg)	1200	Type	*Chain, R4 Studless*
Height mm)	1000	Diameter (mm)	87 dia
Diameter (m)	0.400	Length (m)	914
		MBL (mT)	783.35
Mooring Rope			
Type	*Polypropylene Rope*		
Size (in)	96 dia		
MBL (mT)	154.076		

TABLE 4.
ENVIRONMENTAL DATA

Direction	N	NE	E	SE	S	SW	W	NW
Wind Speed (m/s)	18	18	11	10	13	13	13	13
Current Speed (m/s)								
- Surface	0.80	0.89	0.80	0.62	0.62	0.76	0.85	0.76
- 30m below surface	0.62	0.69	0.62	0.48	0.48	0.67	0.75	0.67
- 3m above bottom	0.50	0.45	0.41	0.35	0.35	0.43	0.48	0.43
Significant Wave height (m)	4.00	4.40	2.00	1.80	2.00	2.00	2.60	2.90
Spectral peak period (s)	9.70	9.90	8.60	8.50	8.60	8.60	9.00	9.10

B. Mooring System

As the positioning system of FSO, the mooring system consists of the mooring chain, mooring rope, and subsea buoy. Those components are based on properties in Table 3. Variations of the mooring system are mooring lines without subsea buoy, mooring lines with one subsea buoy at distances of 605 m, 557.5 m, 550 m, 522.5 m from the anchor, and two subsea buoys at a distance from the anchor 605 m and 476.5 m.

C. Reliability of Mooring System

Analysis of mooring line reliability using the Mean Value First Order Second Moment (MVFOSM) method. In analyzing the reliability of mooring lines, the strength of the mooring lines is important. So, the failure mode that will be reviewed is the maximum tension in the mooring line. A mooring line can failure if the maximum tension that occurs in the mooring line exceeds the breaking strength limit.

III. Results and Discussion

A. Structure Modelling

FSO and shuttle tanker is modeled using software by entering FSO and shuttle tanker coordinates. FSO and shuttle tanker is modeled using software by entering FSO and shuttle tanker coordinates. The front and side view of FSO and shuttle tanker are shown in Figure 1 and Figure 2. The validation parameter used in this study is vessel displacement. The FSO displacement data and model are 128,588.6 and 128,561 tons (full load) and 587,96.11 and 575,89.1 tons (ballast), respectively. Thus, the difference is 0.02% and 2.00%, accepted to continue on the next analysis. The shuttle tanker displacement data and model are 118,644 and 118,787 tons. Thus, the difference is 0.12% and accepted to continue on the next analysis.

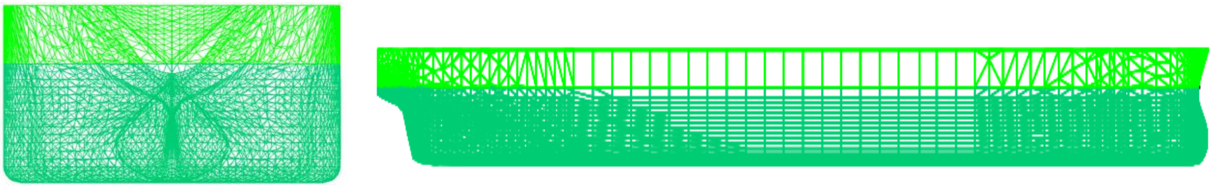

Figure 1. Front and side view of FSO model

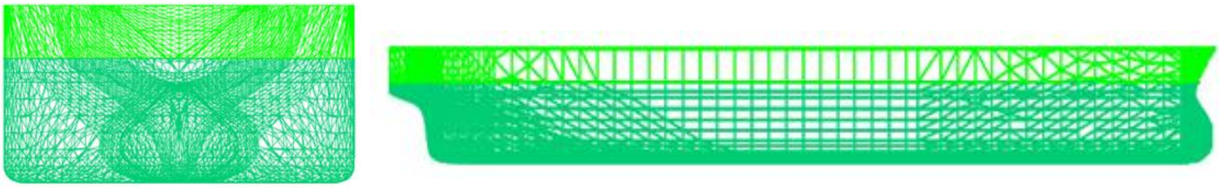

Figure 2. Front and side view of shuttle tanker model

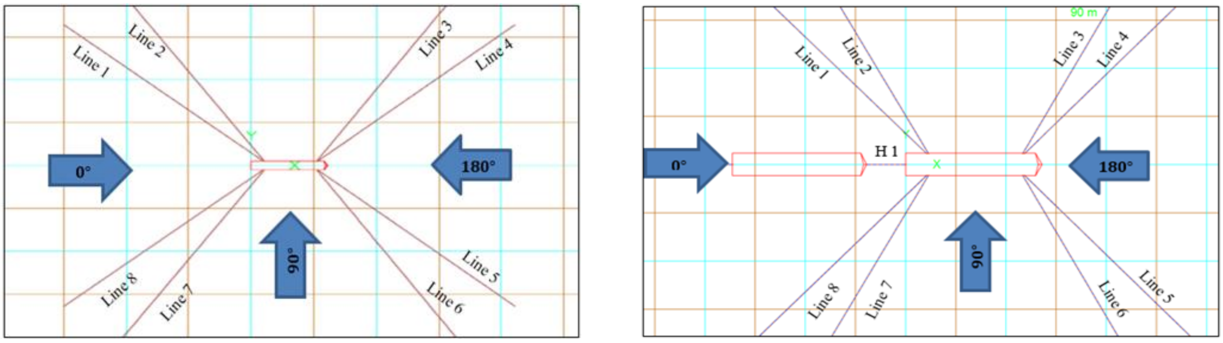

Figure 3. Mooring system model

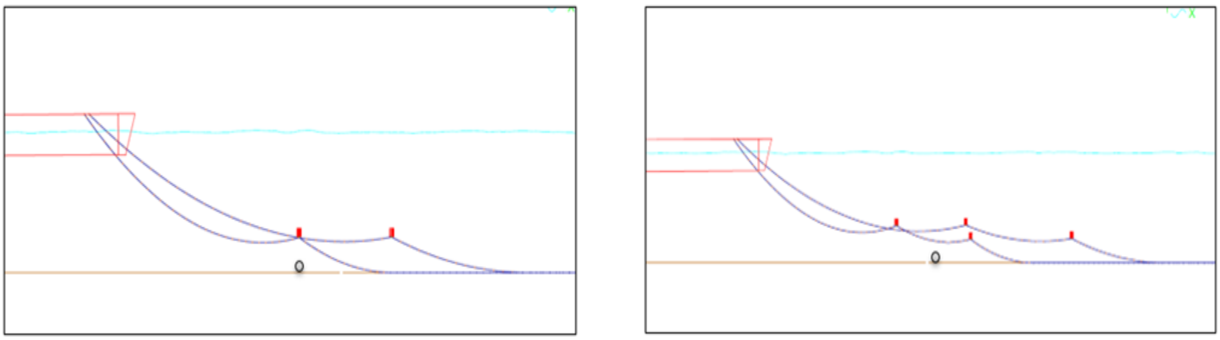

Figure 4. Mooring line with subsea buoy model

The mooring system modeled by the software is modeled in six variations and two conditions, stand alone and offloading condition. Variations of the mooring system are mooring lines without subsea buoy, mooring lines with one subsea buoy at distances of 605 m, 557.5 m, 550 m, 522.5 m from the anchor, and two subsea buoys at a distance from the anchor 605 m and 476.5 m. Variations of mooring lines are displayed in Figure 3 and Figure 4.

TABLE 5.
MAXIMUM RAO FSO

Motion	Unit	RAO Max. Full Load Condition				
		0°	45°	90°	135°	180°
Surge	m/m	0.97	0.69	0.00	0.69	0.97
Sway	m/m	0.00	0.70	0.99	0.70	0.00
Heave	m/m	1.00	1.00	1.45	1.00	1.00
Roll	deg/m	0.01	1.60	2.21	1.59	0.01
Pitch	deg/m	0.79	0.97	0.37	0.93	0.79
Yaw	deg/m	0.00	0.30	0.03	0.32	0.00

Motion	Unit	RAO Max. Ballast Condition				
		0°	45°	90°	135°	180°
Surge	m/m	0.98	0.69	0.00	0.69	0.98
Sway	m/m	0.00	0.70	0.99	0.70	0.00
Heave	m/m	1.00	1.00	1.09	1.00	1.00
Roll	deg/m	0.00	2.20	4.65	2.31	0.00
Pitch	deg/m	0.73	0.78	0.12	0.77	0.73
Yaw	deg/m	0.00	0.32	0.04	0.33	0.00

TABLE 6.
MAXIMUM RAO SHUTTLE TANKER FULL LOAD CONDITION

Motion	Unit	RAO Max.				
		0°	45°	90°	135°	180°
Surge	m/m	0.97	0.68	0.00	0.68	0.97
Sway	m/m	0.00	0.70	0.99	0.70	0.00
Heave	m/m	1.00	1.00	0.45	1.00	1.00
Roll	deg/m	0.01	1.94	2.69	1.92	0.01
Pitch	deg/m	0.85	1.01	0.36	0.88	0.88
Yaw	deg/m	0.00	0.31	0.05	0.32	0.00

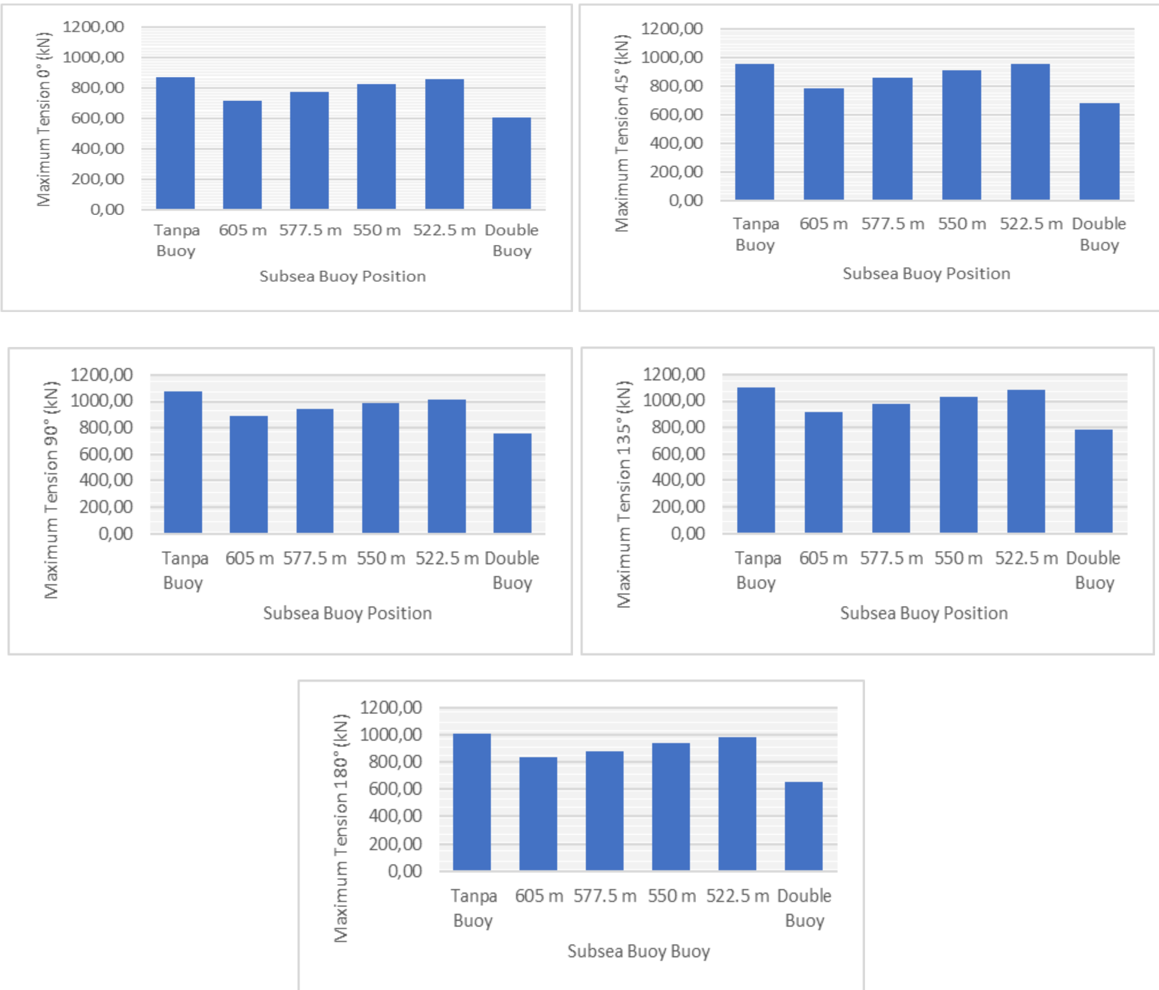

Figure 5. Maximum tension mooring line (offloading condition)

B. Response Amplitude Operator

RAO (Response Amplitude Operator) analysis is carried out on motion characteristics of FSO and shuttle tanker. This analysis is permormed when free floating condition and in 6 degrees of freedom, namely surge, sway, heave, roll, pitch, and yaw. Table 5 and Table 6 shows the RAO of FSO and shuttle tanker during full load and ballast conditions of each degree of freedom.

C. Mooring Line Tension

The analysis of mooring line tension was carried out without using subsea buoy and using a subsea buoy under two conditions, stand alone condition and offloading condition. Mooring line 6 has the highest tension value compared to mooring lines 3, 4, and 5 attached to the subsea buoy. This provides a comparative analysis of the position of the subsea buoy on mooring line 6.

1. Stand Alone Condition

The analysis of the tension on the mooring line was carried out under the condition of no subsea buoy, with a subsea buoy with four variations of position, and two subsea buoys in five wave directions (0 °, 45 °, 90 °, 135 °, 180 °).

Figure 6 shows that the tension on the mooring line is maximum when there is without subsea buoy. The mooring lines with subsea buoys, from smallest to largest, are mooring lines with two subsea buoys, mooring lines with one subsea buoy, and the distance from the anchor are 605 m, 577.5 m, 550 m, 522.5 m.

2. Offloading Condition

The analysis offloading condition of the tension on the mooring line was carried out under the condition of no subsea buoy, with a subsea buoy with four variations of position, and two subsea buoys in five wave directions (0 °, 45 °, 90 °, 135 °, 180 °).

Figure 5 shows that the tension on the mooring line is maximum when there is without subsea buoy. The mooring lines with subsea buoys, from smallest to largest, are mooring lines with two subsea buoys, mooring lines with one subsea buoy, and the distance from the anchor are 605 m, 577.5 m, 550 m, 522.5 m.

D. Offset Analysis

Stand alone and offloading condition are used for analysis. Tables 7 and Table 8 show the offset relations that occurs at the Belida FSO with the position of the subsea buoy. In conditions with one subsea buoy, the further the subsea buoy from the anchor, the greater the offset that appears, at a distance of 605 m from the anchor. However, when compared with the conditions of the two subsea buoys, the offset is greater. The smallest offset occurred in conditions with one subsea buoy at a distance of 522.5 m from the anchor. This situation occurs both in stand alone and offloading conditions in five wave loading directions. The offset that occurs is also in accordance with the API RP 2P criteria, the minimum offset is less than 9.217 m.

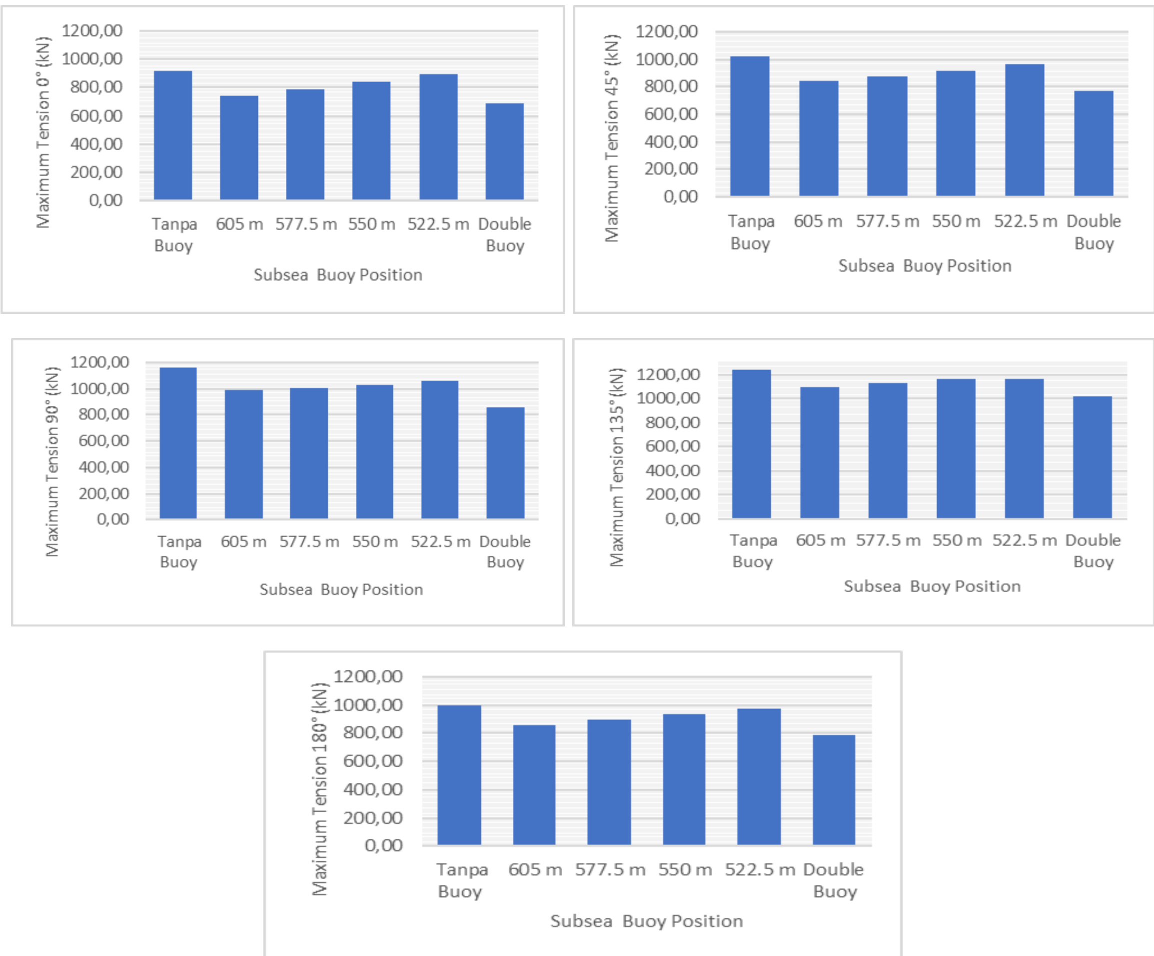

Figure 6. Maximum tension mooring line (stand alone condition)

International Journal of Marine Engineering Innovation and Research, Vol. 8(4), Dec. 2023. 802-809
(pISSN: 2541-5972, eISSN: 2548-1479)

E. Clearance between Mooring Line and Pipeline

The important parameters of adding subsea buoy in the mooring line is to avoid mooring line with pipeline. From table 9, after adding the subsea buoy there is no clashing between mooring line and the pipeline. But the distance meet the criteria of DNV OS E301 is in the variation with one subea buoy with a distance from the anchor 550 m, with one subea buoy with a distance from the anchor 577.5 m, and a condition with two subsea buoy. The largest clearance occurred at two subsea buoys, lines 3 and lines 6 with a value 25.73 m and lines 4 and lines 5 with a value 29.9 m.

TABLE 7.
MAXIMUM OFFSET STAND ALONE CONDITION

Wave Directions	*Offset* x & y	*Maximum Offset* (m)					
		Tanpa *Buoy*	605 m	577.5 m	550 m	522.5 m	*Double Buoy*
0°	x	0.80	1.67	1.05	0.50	0.47	2.53
	y	0.00	0.00	0.00	0.00	0.00	0.00
45°	x	0.34	2.28	1.67	1.02	0.57	3.54
	y	2.84	3.49	3.49	3.46	3.44	3.68
90°	x	0.41	2.34	1.72	1.09	0.46	3.53
	y	2.69	2.90	2.82	2.70	2.62	3.45
135°	x	0.31	2.06	1.47	0.86	0.50	3.08
	y	1.49	1.57	1.30	1.28	1.28	2.13
180°	x	1.43	2.89	2.24	1.58	0.90	4.54
	y	0.14	0.08	0.08	0.08	0.08	0.08

TABLE 8.
MAXIMUM OFFSET OFFLOADING CONDITION

Wave Directions	*Offset* x & y	*Maximum Offset* (m)					
		Tanpa *Buoy*	605 m	577.5 m	550 m	522.5 m	*Double Buoy*
0°	x	0.81	1.67	1.56	1.37	0.66	1.66
	y	0.00	0.00	0.00	0.00	0.00	0.30
45°	x	1.75	3.90	3.19	2.42	1.61	5.18
	y	5.19	5.92	5.62	5.34	5.15	6.40
90°	x	2.41	4.78	3.92	3.14	2.34	6.38
	y	6.72	7.75	7.28	6.84	6.52	8.40
135°	x	3.10	5.94	4.90	4.02	3.19	7.87
	y	7.97	8.91	8.77	8.26	7.85	9.11
180°	x	1.44	3.55	2.67	1.84	1.13	4.89
	y	0.14	0.00	0.00	0.00	0.00	0.00

TABLE 9.
CLEARANCE BETWEEN MOORING LINE AND PIPELINE (STAND ALONE CONDITION)

Line	*Clearance* (m)					
	Tanpa *Buoy*	605 m	577.5 m	550 m	522.5 m	*Double Buoy*
3	0.00	6.51	10.10	12.45	4.77	25.73
4	0.19	17.42	14.41	10.84	3.20	29.90
5	0.19	17.42	14.41	10.84	3.20	29.90
6	0.00	6.51	10.10	12.45	4.77	25.73

TABLE 10.
CLEARANCE BETWEEN MOORING LINE AND PIPELINE (OFFLOADING CONDITION)

Line	*Clearance* (m)					
	Tanpa *Buoy*	605 m	577.5 m	550 m	522.5 m	*Double Buoy*
3	0.00	6.13	10.04	10.58	5.22	24.88
4	0.19	15.92	12.74	10.11	4.39	27.55
5	0.19	15.92	12.74	10.11	4.39	27.55
6	0.00	6.13	10.04	10.58	5.22	24.88

TABLE 11.
RESULT μ_F AND σ_F OF MOORING LINE

Load Case		μ_L	σ_L	μ_s	σ_s	μ_F	σ_F
Stand alone	No Buoy	1032,130	80,541	7681,748	768,175	6649,618	772,386
	One Buoy (522.5 m)	1013,155	60,433	7681,748	768,175	6668,593	770,548
Offloading	No Buoy	871,329	86,151	7681,748	768,175	6810,419	772,991
	One Buoy (522.5 m)	872,617	64,246	7681,748	768,175	6809,131	770,857

TABLE 12.
RELIABILITY OF MOORING LINE

Load Case		β	Φ	P_F	K
Stand alone	No Buoy	8,609	3,209E-17	2,763E-16	1,000,E+00
	One Buoy (522.5 m)	8,654	2,173E-17	1,881E-16	1,000,E+00
Offloading	No Buoy	8,810	5,558E-18	4,897E-17	1,000,E+00
	One Buoy (522.5 m)	8,833	4,549E-18	4,018E-17	1,000,E+00

From table 10, after adding the subsea buoy there is no clashing between mooring line and the pipeline. But the distance meet the criteria of DNV OS E301 is in the variation with one subea buoy with a distance from the anchor 550 m, with one subea buoy with a distance from the anchor 577.5 m, and a condition with two subsea buoy. The largest clearance occurred at two subsea buoys, lines 3 and lines 6 with a value 24.88 m and lines 4 and lines 5 with a value 27.55 m.

F. Reliability Analysis

Mooring line reliability analysis uses the Mean Value First Order Second Moment (MVFOSM) method. In this method, the input required in the calculation is the average value (mean value or first moment) and standard deviation (standard deviation or second moment) of the strength of the structure and the applied load. The reliability index equation can be written as equation 1 [14].

$$\beta = \frac{\mu_F}{\sigma_F} = \frac{\mu_s - \mu_L}{\sqrt{\sigma_s^2 - \sigma_L^2}} \quad (1)$$

If the load and strength are independent and normally distributed, the probability of failure will also be normally distributed (Φ), then the probability of failure can be written as equation 2.

$$P_F = \Phi\left(\frac{\mu F}{\sigma F}\right) = P_F = \Phi(-\beta) \quad (2)$$

After the probability of failure is obtained, the reliability (K) can be calculated using equation 3.

$$K = 1 - \Phi(\beta) = 1 - P_F \quad (3)$$

The reliability of the mooring line is taken from the analysis of stand alone and offloading conditions with an environmental loading direction of 135°, because in these conditions the maximum mooring line tension results are obtained. From the addition of subsea buoys on mooring lines 3, 4, 5, and 6, the highest maximum stress results were also obtained on mooring line 6, so that the mooring line reliability analysis was carried out on mooring line 6. Table 12 shows the reliability of mooring line in stand alone and offloading condition. The probability of failure in the offloading condition without subsea buoy is 4.897E-17 and with subsea buoy (522.5 m) is 4.018E-17. Probability of failure in the stand alone condition without subsea buoy is 2.763E-16 and with subsea buoy (522.5 m) is 1.881E-16. From the probability of failure, the reliability of mooring lines in the offloading condition and stand alone condition without subsea buoy and with subsea buoy (522.5 m) is 1.00. The reliability calculation results set by DNV-OS E301, the results obtained meet the specified reliability criteria, the probability of failure in the intact condition does not exceed 1^*10^{-5}.

IV. CONCLUSION

The probability of failure in the offloading condition without subsea buoy is 4.897E-17 and with subsea buoy (522.5 m) is 4.018E-17. Probability of failure in the stand alone condition without subsea buoy is 2.763E-16 and with subsea buoy (522.5 m) is 1.881E-16. From the probability of failure, the reliability of mooring lines in the offloading condition and stand alone condition without subsea buoy and with subsea buoy (522.5 m) is 1.00. The reliability calculation according to DNV-OS E301, the results obtained meet the specified reliability criteria, the probability of failure in the intact condition does not exceed 1^*10^{-5}.

Acknowledgments

The authors would like to express their sincere gratitude to the Directorate of Research and Community Service of Institut Teknologi Sepuluh Nopember (ITS) Surabaya for supporting the funding of this research. The authors also thank ZEE Engineering for providing the simulation workspace and guidance during the research.

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