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Effect of Mooring System Configuration to Flexible Riser Tension

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***Abstract*— Floating Storage and Offloading is a floating structure that functions as hydrocarbon temporary storage from wells before being distributed to tankers and carried to production facilities on shore. The important components used to support FSO operations are mooring systems and risers. The mooring system is used to limit FSO movement due to environmental loads. Riser was carried out hydrocarbons from the well to FSO This study aims to analyze the effect of mooring system configurations on flexible riser tension. These variations consist of spread mooring, conventional buoy mooring (4 buoy), and two other variations combine spread mooring and conventional buoy mooring. This analysis shows that the mooring system with 4 buoys has the largest flexible riser tension that is 248 kN, while spread mooring has the smallest flexible riser tension, 55 kN. FSO with conventional buoy mooring configuration has the largest offset and spread mooring configuration has the smallest offset. The lazy wave type has smaller riser tension than the free hanging type, which is 4 – 58%.**

Keywords— Bending radius, flexible riser, FSO, mooring system, tension.

I. INTRODUCTION

The energy needs of oil and gas are increasing, causing oil and gas industries to develop technology in exploration, exploitation and production. Exploration and exploitation activities occur in shallow water and deep water with high levels of environmental loads. Therefore, it is necessary to develop technology for offshore structures, especially floating structures. FSO (Floating Storage and Offloading) is a floating structure that functions as hydrocarbon temporary storage from wells before being distributed to tankers and carried to production facilities on shore. Because FSO has a larger storage capacity than others, this unit is advantageous for offshore structures for deep water operations. The important components used to support FSO operations are mooring systems and risers.

The riser carries hydrocarbons from wells to production or storage facilities on the sea surface [1]. The flexible riser is a type of riser that is flexible with low flexural stiffness [2]. Several configurations of flexible risers can be used, including free hanging catenary, lazy wave, steep wave, lazy S, and pliant wave.

Mooring systems are used to limit FSO movement due to environmental loads. This system consists of free hanging lines connecting the floating structure with an anchor or pile on the seabed [3]. Based on recommended practice, the mooring systems usually used in offshore structures are spread mooring, single point mooring, and dynamic positioning [4], [5].

Research about designing risers by considering mooring systems has been analyzed [6], [7]. The results of this research show that risers in shallow water experience greater tension due to the movement of the heave vessel, and the tension decreases when a buoy is added. Mooring lines also affect the riser tension. Another research used the lazy wave and simple catenary riser to study the dynamic response. The results showed that the strength and fatigue of lazy waves were better than other configurations [8]. The stability of risers is analyzed under extreme conditions [9]. A couple dynamic response analysis is conducted of FPSO moorings and risers [10].

This study analyzes maximum tension and minimum bending radius flexible risers due to dynamic load with mooring system variations. This study has four configurations. The first configuration of FSO is spread mooring. The second is the conventional buoy mooring type. The other configurations are combination spread mooring and conventional buoy mooring. Flexible risers used in this study are free hanging and lazy wave types.

II. METHOD

A. FSO Model

The FSO model has a draft of 14.9 meters based on the characteristics described in Table 1. FSO 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% [11]. After validation, the simulation will analyze the hydrostatic and response amplitude operator (RAO). Two load conditions of FSO are analyzed: full and ballast conditions.

FSO is also modeled in a moored condition. There are two conditions: without a riser and with riser modeling. The main object in this research is the riser, modeled with the properties shown in Table 2. Table 4 displays environmental load consisting of wind, current, and waves varied from eight directions.

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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.
RISER DATA

Flexible ID (mm)	*250*
Flexible OD (mm)	350
Internal Volume (1/m)	49.07
External Volume (1/m)	95.68
Weight in Air (te/m)	0.181
Weight in Water(te/m)	0.083
Bending Stiffness(kN.m^2)	117.188
Axial Stiffness(kN)	700000
Torsional Stiffness(kN.m^2)	80
Minimum Bending Radius (m)	3.675
Total length (m)	134

TABLE 3.
MOORING SYSTEM DATA

Floater		**Mooring Chain**	
Float OD(mm)	1200	Type	*Chain, R4 Studless*
Length (mm)	1000	Diameter (mm)	87 dia
Material Density(te/m^3)	0.400	Length (m)	914
Volume (m^3)	1.035	MBL (mT)	783.35
Mass(te)	0.439		
Displacement (te)	1.061		
Mooring Line		**Buoy**	
Type	*Polypropylene Rope*	Outer Diameter (m)	7.6
Size (in)	12 dia	Depth (m)	3.0
MBL (mT)	1005.41	Draft (m)	1.3
Mooring Line			

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

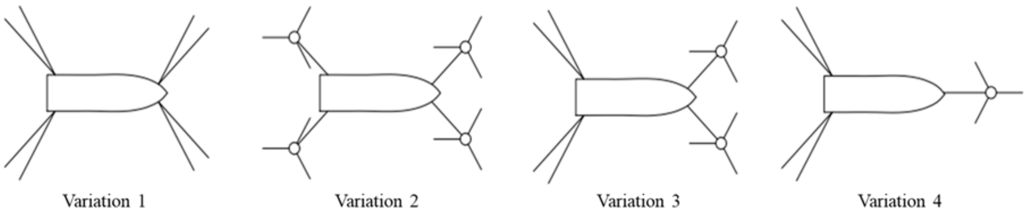


Figure 1. Variations of mooring system configuration

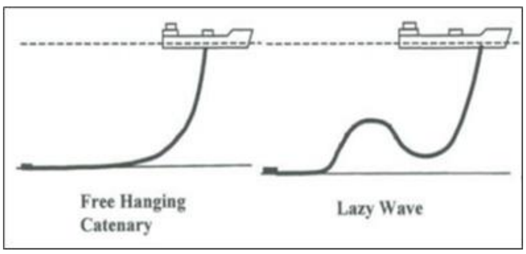


Figure 2. Flexible riser configurations

B. Mooring System

As the positioning system of FSO, the mooring system consists of the floater, mooring chain, line, and buoy. Those components are based on properties in Table 3. The mooring system configuration shown in Figure 1 used in this study has four variations: spread mooring, conventional buoy mooring, and two others, combination spread and conventional buoy mooring.

C. Riser Configuration

This research focuses on studying the flexible riser. The first configuration is a hanging catenary commonly used in offshore structures. Meanwhile, the other is a lazy wave type configuration that puts additional buoys along the riser to keep the touchdown point from the structure movement. The second configuration is commonly used for FSO in environmental condition with high waves. The configuration of risers in this study is shown in Figure 2.

III. Results and Discussion

A. Structure Modelling

FSO is modeled using software by entering FSO coordinates. The front and side view of FSO are shown in Figure 3. Validation parameter used in this study is vessel displacement. The displacement data and model are 118,644 and 118,787 tons, respectively. Thus, the difference is 0,12% and accepted to continue on the next analysis.

Mooring systems modeled by software in 4 variations as displayed in Figure 4. Variation 1 FSO is moored with spread mooring which consists of eight lines. Variation 2 FSO is moored with four buoys, FSO is moored to buoy by rope, and buoys are moored to seabed by chain. Variation 3 FSO was moored by spread mooring and conventional buoy mooring combinations, where two buoys moored at the front of FSO. Variation 4 FSO was moored by spread mooring and conventional buoy mooring combinations, whereas the front of FSO was moored by a buoy. The Minimum length of the mooring

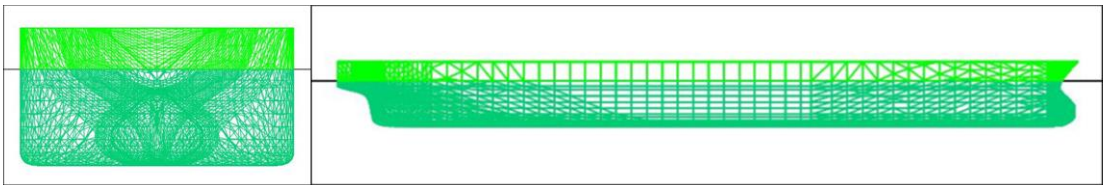


Figure 3. Front and side view of FSO model

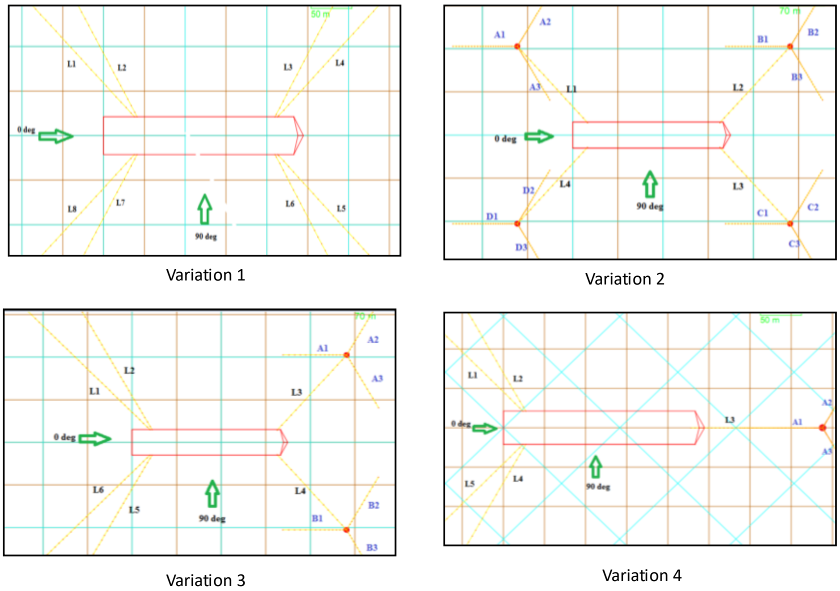


Figure 4. Mooring system model

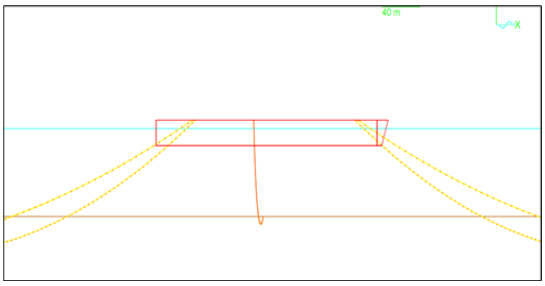


Figure 5. Riser model

line based on Faltinsen [12]. Meanwhile, a flexible riser is modeled as shown in Figure 5.

B. Response Amplitude Operator

RAO (Response Amplitude Operator) analysis is performed on motion characteristics of FSO This analysis is carried out when free floating condition and in 6 degrees of freedom, namely surge, sway, heave, roll, pitch, and yaw [13]. Figure 6 shows the RAO during full load and ballast conditions of each degree of freedom.

The most dominant motion is roll either in full load or ballast condition. In the ballast condition, RAO in roll motion exceeds 4.64 deg/m, while in full load condition, the RAO reaches 2.21 deg/m. Other motions showed the same result. Ballast condition results are higher than full load condition. The highest RAO is given by 90° load direction followed by quarter load directions (45° and 135°) and no movement from 0° and 180° load directions.

Heave is the second most dominant motion for this FSO. Different from roll, RAO for heave is highest in full load rather than ballast condition. For full load. RAO is 1.44 m/m in the frequency 0.6 rad/s with the load direction coming from 90°. Meanwhile, 45° and 135° load directions give the highest RAO about 1.0 m/m in 0.1 rad/s of frequency.

Surge is dominant with loads from 0 (stern) and 180 (bow) about 0.97 m/m, while the 90 loads almost give zero impact on the vessel movement. Meanwhile, the quarter direction (45° and 135°) gives the RAO result around 0.69 m/m. Full load and ballast conditions do not differ significantly, with a difference of around 1%. Translation movement in y direction or sway is significantly influenced by load from direction 90°. The peak of RAO is affected by 0.1 rad/s wave frequency. The highest RAO is 0.99 m/m, followed by 0.699 m/m.

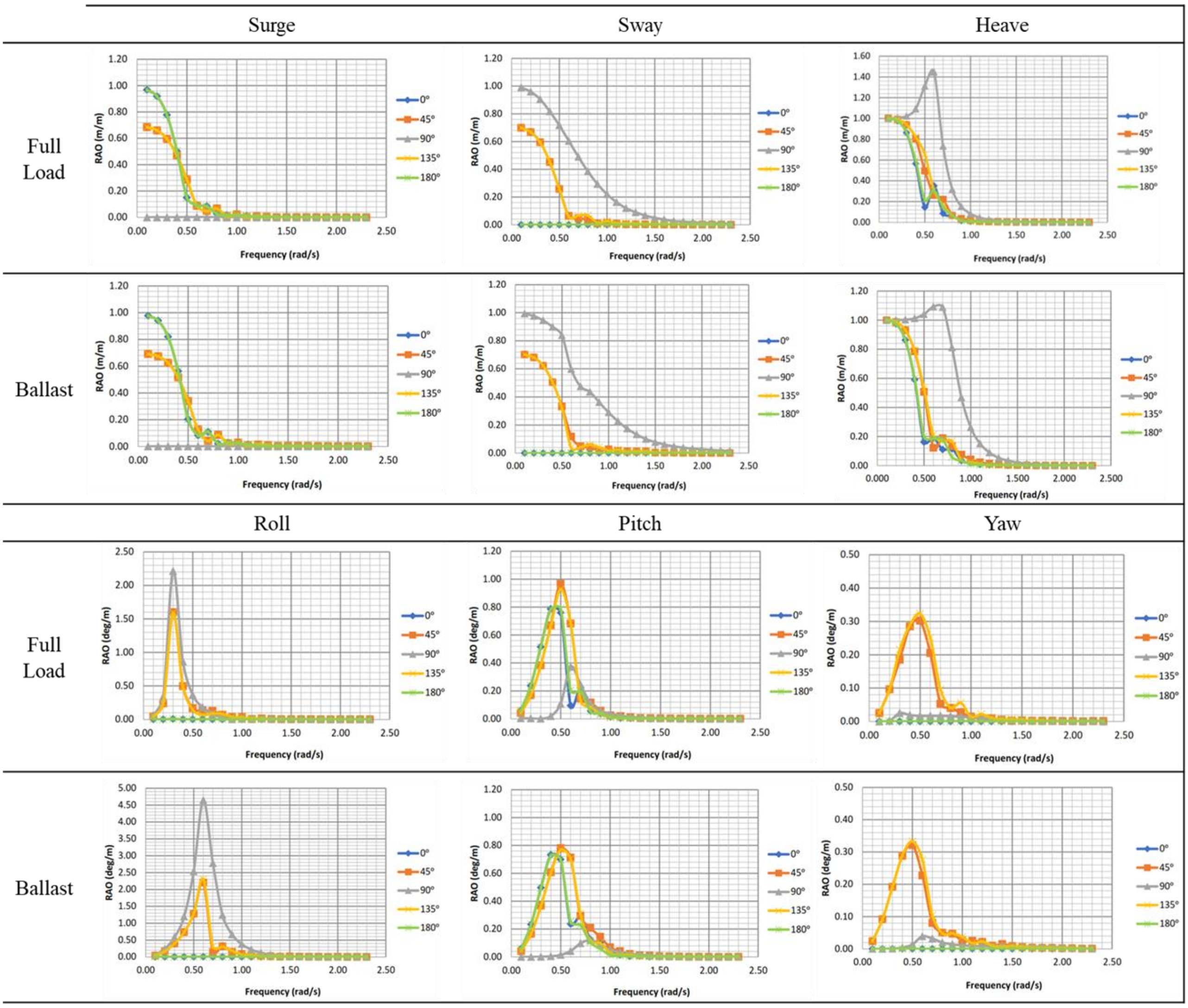


Figure 6. RAO Motions in full load and ballast condition

TABLE 5.
RESULTS OF MOORING LINE TENSION IN EACH MOORING SYSTEM CONFIGURATION

	Variation 1 (kN)				
Line	0°	45°	90°	135°	180°
L1	965.25	804.5	807.79	835.22	922.69
L2	946.35	769.94	785.65	818.83	923.86
L3	872.82	842.37	811.49	755.37	922.07
L4	863.99	847.65	824.35	784.34	942.28
L5	859.67	936.47	1083.02	1100.87	937.55
L6	859.67	939.65	1118.7	1147.81	915.41
L7	959.98	1137.7	1231.14	1098.61	915.41
L8	967.43	1088.73	1139.81	1047.34	924.88
	Variation 2 (kN)				
	0°	45°	90°	135°	180°
L1	418.46	193.04	136.45	424.83	465.52
L2	169.12	475.29	84.28	155.11	534.97
L3	148.25	834.41	753.95	987.55	540.99
L4	423.46	830.71	771.05	849.72	449.17
A1	709.24	556.71	350.66	401.29	572.32
A2	364.42	348.65	301.25	387.48	1410.57
A3	321.09	381.85	411.71	432.62	1124.1
B1	694.46	476.5	312.58	336.43	515.46
B2	379.19	379.99	382.13	323.14	906.01
B3	384.16	335.79	407.3	532.74	1462.29
C1	883.28	332.6	194.33	229.21	525.43
C2	351.31	212.89	171.1	212.93	1511.55
C3	399.89	1041.78	962.7	1275.83	890.24
D1	717.46	929.68	853.91	910.42	491.42
D2	293.78	197.14	172.99	201.17	1326.57
D3	372.08	774.16	766.37	796.09	1692.23
	Variation 3 (kN)				
	0°	45°	90°	135°	180°
L1	477.96	361.06	349.75	311.45	422.54
L2	506.55	360.87	346.82	334.92	462.58
L3	527.96	545.37	522.25	444.65	708.28
L4	529.70	585.44	850.24	852.36	705.36
L5	516.63	735.92	825.06	766.61	468.53
L6	481.25	764.47	691.66	624.09	424.33
A1	271.92	239.76	242.34	298.29	531.18
A2	754.59	763.16	709.97	642.23	1128.77
A3	199.41	213.34	317.53	614.89	1381.92
B1	266.60	249.02	198.83	167.65	531.50
B2	194.11	216.58	208.53	201.43	1486.53
B3	756.16	979.32	1101.70	1116.28	1076.69
	Variation 4 (kN)				
	0°	45°	90°	135°	180°
L1	501.74	376.39	211.26	196.25	272.36
L2	332.89	433.53	231.48	201.08	325.73
L3	277.29	603.70	1157.41	1259.03	1032.91
L4	339.15	789.79	1206.69	1436.33	346.40
L5	510.23	1114.02	607.40	823.55	280.59
A1	312.89	197.04	142.40	109.69	658.40
A2	369.18	820.98	838.17	737.29	1217.65
A3	368.74	1051.39	1160.58	1291.07	1432.87

For the rotational motion, pitch and yaw are mostly affected by waves from 45° and 135°. The highest pitch motion from all directions occurs around frequency 0.4 – 0.6 rad/s around 0.97, 0.78, and 0.37 deg/m due to waves from 45°, 0°, and 90°, respectively. These happen in full load. Meanwhile, the ballast condition gives the highest result around 0.3 deg/m in frequency 0.5 rad/s for yaw motion. Waves from 90° only give small motion below 0.04 deg/m, while waves from 0° and 180° do not give any movement to FSO in free floating conditions.

C. Mooring Line Tension

Based on API criteria, the mooring line's Safety Factor (S.F.) is not below 1.67. S.F. is based on the mooring system data in Table 3. This analysis was carried out with five load directions including 0°, 45°, 90°, 135° and 180°. The following is the result of mooring line tension.

Table 5 displays the result of the mooring line tension analysis. All mooring line tensions satisfy the API criteria. Variation 1 gives the highest mooring line tension due to loads from 90°. The greatest mooring line tension occurs at line L7, about 1231 kN, which directly contact with the loads from 90°. In contrast, the other variations give the highest result from the 180° load direction. The lines with the greatest tension occur at D3, B2, and A3 for the second, third, and fourth variations, respectively. Variation 2 is the greatest than other variations, reaching 1692 kN, while the third and fourth variations have almost the same tension around 1450 kN.

D. FSO Offset

The results of the FSO offset for each mooring configuration are shown in Figure 7. The highest offset occurs for the second variation of the mooring system due to loads from a 45° direction. The offset is 3.43 m on the X ordinate and 30.68 m on the Y ordinate. The smallest offset occurs in mooring system variation 1 with 0° load direction, and the offset is 0.48 m on X ordinate and 0.08 m on Y ordinate.

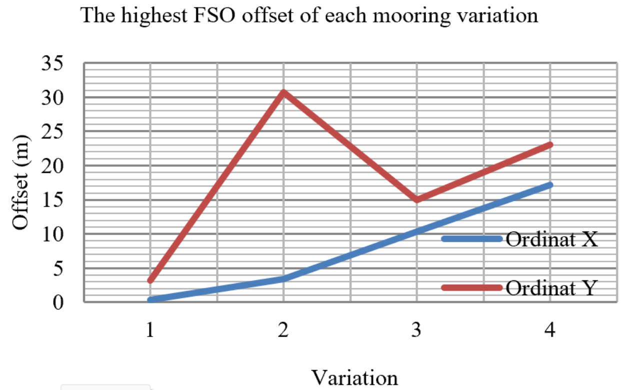
The use of buoys in the mooring system will give a higher offset. These results also follow mooring line tension; the further offset of FSO will lead to greater mooring line tension. Thus, the first variation may be a better configuration due to simple configuration.

E. Flexible Riser Tension and Bending Radius

The important parameters of flexible tension are tension and bending radius. The failure of those two will affect the overall riser integrity. This research anlyze in two conditions of FSO that are stand alone and offloading or when shuttle tanker was moored to FSO

TABLE 6.
RESULTS OF FSO OFFSET FOR EACH LOAD DIRECTION AND VARIATION

		Offset (m)			
		Variation 1	Variation 2	Variation 3	Variation 4
0	X ordinat	0.48	13.53	6.30	14.31
	Y ordinat	0.08	2.49	0.21	0.37
45	X ordinat	0.31	3.43	10.28	17.15
	Y ordinat	3.15	30.68	14.96	23.01
90	X ordinat	0.37	3.09	11.38	27.33
	Y ordinat	3.40	27.17	15.80	27.89
135	X ordinat	0.65	11.81	10.59	24.53
	Y ordinat	2.29	22.49	12.17	26.48
180	X ordinat	0.95	10.07	13.02	26.38
	Y ordinat	0.08	1.46	0.25	0.88



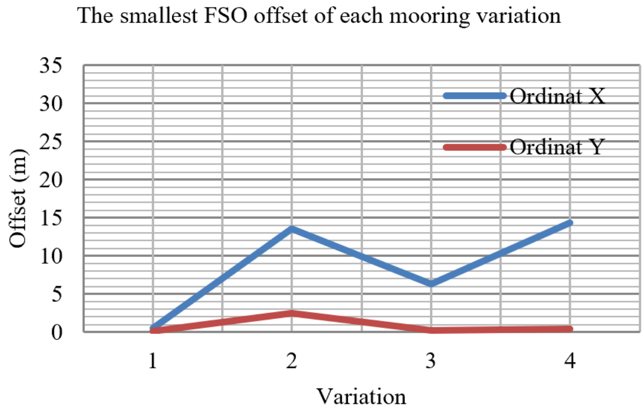


Figure 7. The highest and smallest offset of FSO

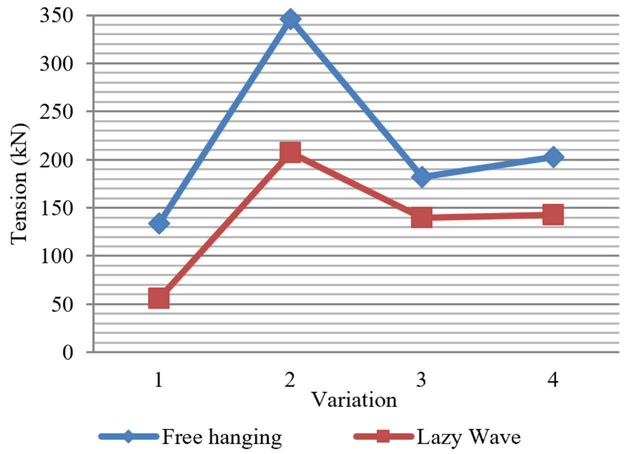


Figure 8. Flexible riser tension in offloading condition due to loads from 45°

TABLE 7.
RESULTS OF MAXIMUM BENDING RADIUS

Heading	MBR in stand alone condition (m)								MBR in offloading condition (m)							
	Variation 1		Variation 2		Variation 3		Variation 4		Variation 1		Variation 2		Variation 3		Variation 4	
	FH	LW	FH	LW	FH	LW	FH	LW	FH	LW	FH	LW	FH	LW	FH	LW
0°	7.2	6.4	4.9	6.3	7.0	6.3	7.1	6.4	7.0	7.5	3.6	6.1	4.0	6.7	4.0	6.7
45°	7.9	7.0	6.3	7.8	8.8	7.3	11.9	12.1	6.0	7.7	5.3	7.2	5.1	7.7	6.8	8.5
90°	8.2	7.2	6.9	8.1	9.3	8.5	17.7	12.7	6.2	7.5	5.8	7.0	6.1	8.1	7.2	9.2
135°	8.7	7.5	6.6	7.7	10.1	8.7	23.3	14.4	6.8	8.8	7.4	7.3	6.4	8.1	8.1	10.0
180°	7.7	6.9	5.3	6.8	7.3	6.7	7.8	7.2	5.8	8.3	4.4	6.4	4.8	7.2	5.1	7.4

Flexible risers that are used in this analysis are free hanging and laxy wave. This analysis was carried out with 5 load direction 0°, 45°, 90°, 135°, and 180°.

The results were then checked with the safety factor criteria based on API 17B Recommended Practice for Flexible Pipe and API 17J Specification for Unbonded Flexible Pipe. Maximum bending radius (MBR) must be above 1.5 of the highest MBR in operating conditions. Based on the data, the failure tension limit of this research is 1884 kN, while the minimum MBR is 3.675 meters.

Variations of mooring systems affect the flexible riser tension. The greatest tension occurs in type 2, where FSO is moored by conventional buoy mooring (4 buoys) and uses free hanging type to the flexible riser. The tension is around 346 kN. Figure 8 displays the flexible riser tension when FSO offloading due to loads from 45°.

The bending radius is the radius measured inside the bend after bending. A flexible riser with the smallest bending radius is Variation 2, where a type of riser is free hanging. In stand-alone conditions, the result of the bending radius is 4.90 m, and in offloading conditions, it is 3.63 m. This result does not fulfill API criteria. Table 7 shows that the flexible riser with free hanging type in Variation 2, Variation 3, and Variation 4 did not fulfill API criteria, while the lazy wave type for all variations fulfill API criteria.

IV. CONCLUSION

From the analysis and discussion the conclusions are:

1. The maximum tension of mooring system variation 1 (spread mooring) is 1231 kN with 90° load direction, and mooring system variation 2 (conventional buoy mooring) has a maximum tension of 1692 kN that occurs at the anchor chain with 180o load direction. Mooring system variation 3 (2 buoys) has a maximum tension of 1487 kN with 180° load direction. In comparison, mooring system variation 4 (1 buoy) has a maximum tension of 1432 kN with 180o load direction. The largest FSOs offset occurs to mooring system variation 2 (4 buoys), 3 m on the X, and 31 m on the Y ordinate.
2. The greatest riser tension occurs in the mooring system variation two, where the FSO has the greatest offset. FSO offset follows the tension result because the FSO moves freely. The greater offset will lead to riser tension. The greatest tension occurs in the 45° load direction, 346 kN. The lazy wave type has smaller tension than free hanging. The difference is around 4 – 58%.

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