

# Design and reliability analysis of accommodation work barge mooring configuration at a tension leg platform in Makassar Strait, Indonesia

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**Abstract.** An Accommodation Work Barge in Makassar Strait attaches to a Tension Leg Platform (TLP), a floating offshore platform operating in deep-water oil and gas field for a well intervention project. The mooring system are tied up to the north mooring lines of the vessel, whilst hawsers from the TLP connected to the south lines of the vessel. The TLP is fitted with two "TH" lines on its south side. However, these "TH" lines fail due to the unknown reason. The purpose of this study is to evaluate mooring performances to support the TLP operation by using API RP2SK recommendation, which suggests line tension limit, TLP offset, and minimum clearance between facilities. This study assesses reliability index ( $\beta$ ) of the recommended design to evaluate whether the TH lines are required or could be eliminated. Mooring analysis is performed using ORCAFLEX for intact and damaged condition, while Monte Carlo simulation is performed to get system failure probability with minimum breaking strength ratio (%MBS) as required parameter. From the results, it is found that TH lines could be eliminated, as they do not affect significantly to the system. The analysis delivers a very secure index ( $\beta=14.676$ ) with probability of failure below 10-5.

## 1 Introduction

The purpose of this paper is to verify the mooring performances of the vessel connected to the TLP in Makassar Strait, Indonesia and the impact of the mooring forces on the TLP offset performances. More precisely to evaluate required mooring pattern, configuration, and properties, provide separation distance to ensure safe clearance between facilities, and provide recommendation as to whether TH mooring legs are required or could be eliminated. This study also provide basis for required mooring accessories to be prepared.

One criteria in designing a floating offshore structure is about its mooring system [1,2]. A Tension Leg Platform (TLP) as one of the floating offshore oil and gas platform is suit to operate in deep water (1000 m – 1500 m). Once in its lifetime, a well intervention usually needed to make an improvement to the well. This long process needs extra facilities to support accommodation.

An Accommodation Work Barge (AWB) is working at TLP in Makassar Strait, Indonesia for a well intervention project. The system installed with 4 mooring lines D1 to D4 which tied up to the north of the vessel, whilst 4 hawser lines connect TLP to the south lines of the vessel and is fitted with 2 lines TH1 and TH2 on the south side. However, the TH lines are having a failure issue due

to unknown reason. Therefore, a mooring analysis performed to evaluate required mooring pattern, properties to support this operation using American Petroleum Institute Design and Analysis of Station keeping Systems for Floating Structures (API RP2SK) recommendation. The criteria suggest the line tension limit, TLP offset, and minimum clearance between facilities. This API practices requires that the design load for floating platform is 100yr, return period wave height combined with associated wind and current [3,4].

To achieve those objectives, the mooring analysis will determine:

- Recommended mooring pattern and vessel position.
- Hawser configuration (length, diameter, breaking load)
- Require length of mooring line out of the fairlead
- Initial line tension
- Limiting environment for storm conditions (100-YRP)
- Results comparison of line tension, TLP offset, and clearance with and without TH1 and TH2 mooring lines to ensure that the system is within acceptable limit for both conditions.

In this paper, reliability analysis will provide reliability index ( $\beta$ ) of design recommendation whether TH mooring lines are required or could be eliminated. This analysis will cover the presence of uncertainty in its structural capacity and the environmental load that occur

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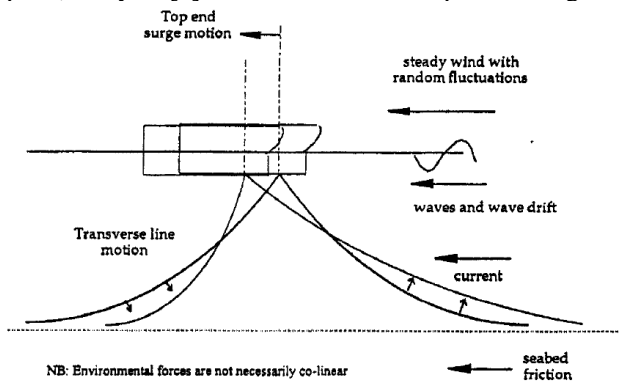
[5]. Therefore, we can assess the probability of failure in this system and know how secure the system is.

## 2 Study Cases

### 2.1 Mooring analysis

To evaluate the proposed mooring system of the AWB at the north face of the TLP, we have run a mooring analysis following the API RP 2 SK recommendations. The mooring analysis has been performed with the computer program ORCAFLEX from Orcina using a coupled model of the TLP and the AWB.

There are various loading mechanisms acting on a moored floating vessel [1]. For this study, the excitation forces caused by current are assumed temporarily constant, with spatial variation depending on the current profile and direction with depth. Wind loading is taken as constant, at least, in initial design calculations, though gusting can produce slowly varying responses. Wave forces result in time-varying vessel motions in the six rigid body degrees of freedom of surge, sway, heave, roll, pitch, and yaw [2]. This illustration as depicted in Fig. 1.



**Fig. 1.** Environmental forces on a moored vessel

The drag loads due to translational velocity of the sea and air past the vessel are calculated using the standard OCIMF method outlined below [6]. This method calculates the surge, sway, and yaw drag loads on a stationary vessel. ORCAFLEX extends this to a moving vessel by replacing the current (or wind) velocity used in the OCIMF method with the relative translational velocity of the current (or wind) past the vessel. More precisely, the relative velocity is that of the current (or wind), relative to the low frequency primary motion of the vessel, at the current (or wind) load origin. In other words, the relative velocity includes the current but not the waves, and it includes the low frequency primary motion of the vessel, but not the wave frequency motion or the superimposed motion.

The drag loads due to surge and sway relative velocity are calculated as given by the following OCIMF formulae.

$$\begin{aligned} f_x &= \frac{1}{2} C_{surge} \cdot \rho |v|^2 A_{surge} \\ f_y &= \frac{1}{2} C_{sway} \cdot \rho |v|^2 A_{sway} \\ m_z &= \frac{1}{2} C_{yaw} \cdot \rho |v|^2 A_{yaw} \end{aligned} \quad (1)$$

Where:

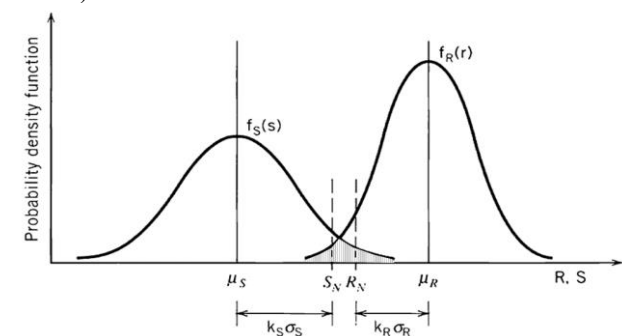
- $f_x, f_y,$  and  $m_z$  are the drag force in the x- and y- directions and moment about z- direction
- $C_{surge}, C_{sway}$  and  $C_{yaw}$  are the surge, sway and yaw drag coefficients for the current or wind direction relative to the low frequency vessel heading
- $\rho$  is the water density (for current) or air density (wind)
- $v$  is the relative velocity of the sea or air past the vessel

For the AWB, wind and current drag coefficients, were used from the vessel's data [7]. The drift forces and vessel motions were obtained by a hydrodynamic analysis using MOSES computer program.

For the TLP, wind and current drag coefficients also used from the TLP data. TLP hydrodynamic motions RAOs and Quadratic Transfer functions are generated by a hydrodynamic analysis using MOSES. The TLP actual mechanical properties (actual tendons and riser tensions) are given by TLP data. The tendons and risers' tensions are used to define the TLP motions and offsets, but it is not the intention of this paper to verify the tension in the riser and tendons.

### 2.2 Reliability analysis

To assess probability of failure of the recommended design, we performed reliability analysis using *Monte Carlo Simulation* [5]. This analysis is used to cover numerous sources of uncertainty in the load and resistance related parameters of a designed structure. (See Fig. 2 below).



**Fig. 2.** Load and resistance distribution

Where the uncertainties in the load and resistance variables are expressed in the form of the probability density functions, we can express the measure of risk in terms of the probability of the failure event or  $P(R < S)$  as this formula:

$$\begin{aligned} p_f &= P(\text{failure}) = P(R < S) \\ &= \int_0^\infty \left[ \int_0^s f_R(r) dr \right] f_S(s) ds \\ &= \int_0^\infty F_R(s) f_S(s) ds \end{aligned} \quad (2)$$

Where  $F_R(s)$  is the Cumulative Distribution Function of R evaluated at s. The probability of failure in terms of the safety index can be obtained as:

$$p_f = \Phi(-\beta) = 1 - \Phi(\beta) \quad (3)$$

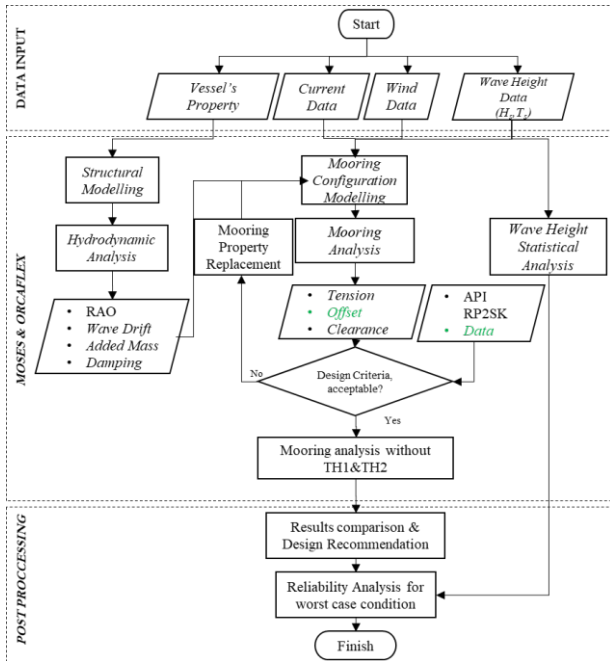
Load parameter is constant, and the resistance parameter is based on line tension minimum breaking load (MBL). The event failure is when loads occur on the line are greater than its capacity. So, the performance function [5] is written as:

$$Z=g(R,S) = R - S \quad (4)$$

We performed 50 simulations to assess distribution of the MBL percentage for each simulation.

### 2.3 Methodology

The step of this study is shown in flowchart Fig. 3 below.



**Fig. 3.** Flowchart of the study

Mooring analysis performed for intact and damaged condition using API recommendation for dynamic analysis. For intact condition, dynamic analysis safety factor for tension limit is 60%, and offset limit is 3% water depth. For damage condition, it is 80% MBL and 5% water depth. The horizontal clearance recommendation between facilities is 10 m for both operating and storm condition [3].

## 3 Results and Discussion

### 3.1 Mooring analysis Results

The simulations are performed for eight different environmental heading cases as shown in Table 1 [8].

**Table 1.** Environmental heading cases, 100YRP

100 - Year Return Storm	N	NE	E	SE	S	SW	W	NW	Omni
Significant Wave									
Height (Hs) (m)	3.0	2.5	2.4	1.2	1.9	1.4	1.9	1.9	3.0
Peak Period (Tp) (s)	8.3	7.6	7.4	5.3	6.5	5.6	6.7	6.6	8.3
Hmax (m)	5.5	4.6	4.4	2.2	3.4	2.5	3.6	3.5	5.5
Thmax (s)	7.8	7.2	7.0	5.0	6.2	5.3	6.3	6.3	7.8
1-hr wind speed (m/s)	21.2	18.7	18.0	11.7	15.5	12.7	15.9	15.7	21.2
Current Speed (m/s)	1.31	0.78	0.78	0.78	1.31	0.78	0.78	0.78	0.78

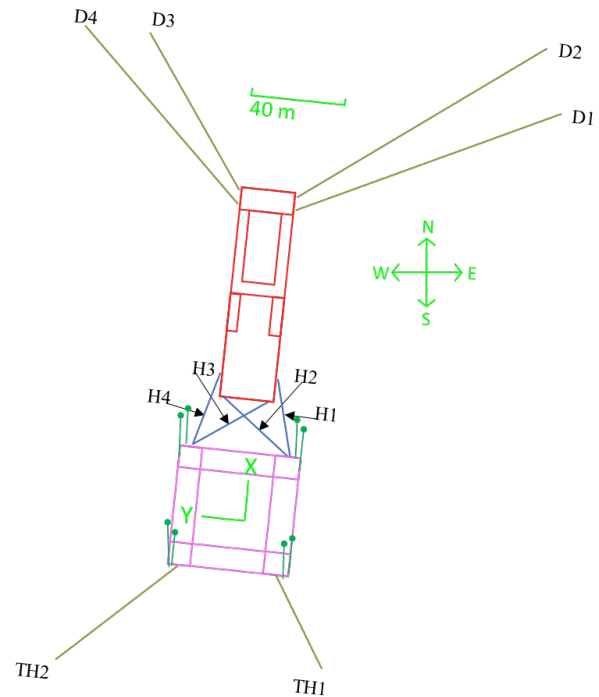
\*Notes :

\*Wave directions refer to the direction from which the waves come from

\*The wave spectrum type is JONSWAP spectrum with a peak enhancement factor of (γ) 2.5:

For each dynamic analysed case, a time domain simulation is performed with 3-hour duration each and a time step of 0.1-s [1]. The analysis using ORCAFLEX

software is performed for the coupled model of TLP and AWB (see Fig.4).



**Fig. 4.** Coupled model of TLP and AWB

The analysis results present the maximum tension in the vessel and TLP mooring lines, the vessel and TLP offset and motions as well as the clearance between the two vessels. The tendon and riser tensions are excluded.

The model has been validated by checking its stability and response frequency in regular waves.

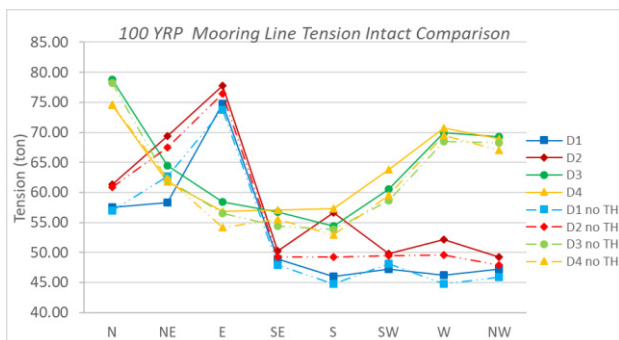
From the analysis, it is recommended to change the AWB mooring lines connected to the TLP with new IWRC 54mm wires with MBL 174 tonnes from EEIPS 38 mm wires with MBL 90 tonnes [9].

After this replacement in the mooring properties to increase strength, we compared the results using dynamic analysis with and without TH1 & TH2 lines for intact and damaged condition. The criteria which been compared is the maximum line tension, TLP offsets and clearance between two vessels.

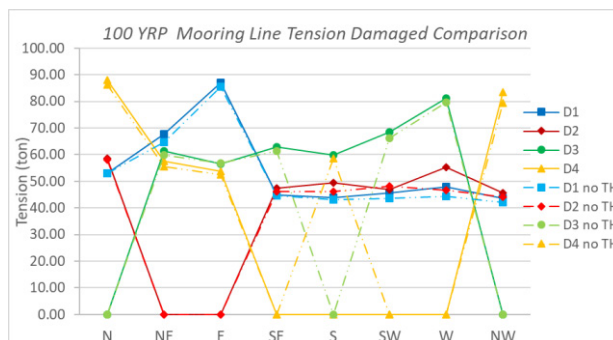
#### 3.1.1 Line Tension

Results comparison between line tension for each condition show in figures below. The vertical coordinate represents value of the line tension in tonnes and horizontal coordinate represent each environmental heading cases. Results for analysis where TH lines are included is connected by continuous lines and for condition where TH lines are excluded is connected with dotted lines.

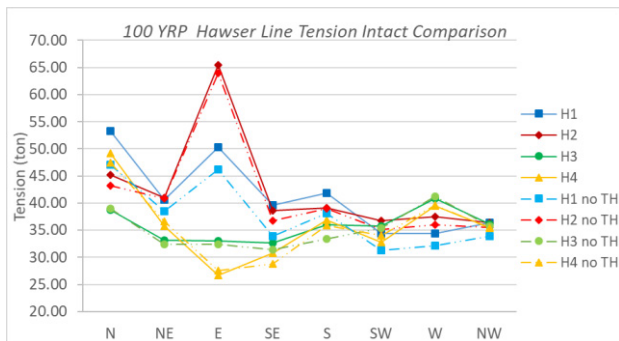
For intact condition, the graph shows the line tension comparison for mooring lines connected to the north of vessel (D1 – D4) as shown in Fig.5, and for hawser lines (H1 – H4) which connect the vessel to the TLP as shown in Fig.6 below.



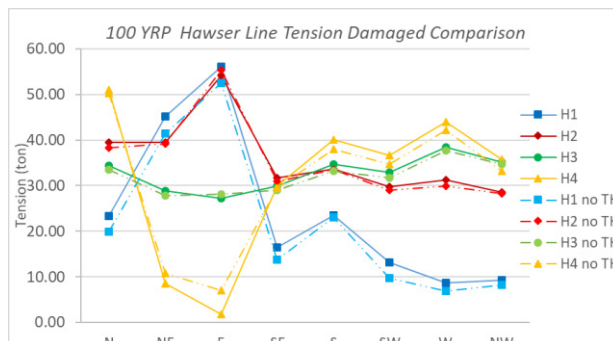
**Fig. 5.** D1 – D4 line tension comparison, intact condition



**Fig. 7.** D1 – D4 line tension comparison, Damaged condition



**Fig. 6.** H1 – H4 line tension comparison, intact condition



**Fig. 8.** H1 – H4 line tension comparison, Damaged condition

Whilst for damaged condition is shown in Fig.7 and Fig.8. For these graph, zero (0) value of the line tension means condition for the failed line which occur at different lines depends on each environmental heading case.

From the graphs above, we see that there is no significant effect to the line tension for intact or damaged condition, whether TH lines is included or excluded. Detailed results for both conditions shown in Table 2 below.

**Table 2.** Line tension results comparison, with and without TH1&TH2

Tension Results: 100 YRP												
Environment Heading	Failed Line No	Fairlead				FOS				FOS		
		Line No		Max t	Tension %MBS	Achieved Criteria 2SK		Achieved Criteria 2SK				
TH Line	With TH	No TH	With TH	No TH	With TH	No TH	With TH	No TH	With TH	No TH	No TH	
North	intact		D3	D3	78.8	78.2	45.3%	44.9%	2.21	1.67	2.22	2.00
	Damaged	D3	D3	D4	D4	87.9	86.2	50.5%	49.6%	1.98	1.25	2.02
North East	intact		D2	D2	69.4	67.5	39.9%	38.8%	2.51	1.67	2.58	2.00
	Damaged	D2	D2	D1	D1	67.6	64.5	38.8%	37.1%	2.57	1.25	2.70
East	intact		D2	D2	77.8	76.4	44.7%	43.9%	2.24	1.67	2.28	2.00
	Damaged	D2	D2	D1	D1	87.1	85.6	50.0%	49.2%	2.00	1.25	2.03
South East	intact		D4	D4	57.1	55.6	32.8%	31.9%	3.05	1.67	3.13	2.00
	Damaged	D4	D4	D3	D3	62.8	61.3	36.1%	35.2%	2.77	1.25	2.84
South	intact		D4	D3	57.3	53.8	32.9%	30.9%	3.04	1.67	3.23	2.00
	Damaged	D4	D3	D3	D3	59.8	58.5	34.3%	33.6%	2.91	1.25	2.97
South West	intact		D4	D4	63.8	59.5	36.7%	34.2%	2.73	1.67	2.92	2.00
	Damaged	D4	D4	D3	D3	68.6	66.1	39.4%	38.0%	2.54	1.25	2.63
West	intact		D4	D4	70.7	69.5	40.6%	40.0%	2.46	1.67	2.50	2.00
	Damaged	D4	D4	D3	D3	81.2	79.5	46.7%	45.7%	2.14	1.25	2.19
North West	intact		D3	D3	69.3	68.2	39.8%	39.2%	2.51	1.67	2.55	2.00
	Damaged	D3	D3	D4	D4	83.4	79.4	47.9%	45.6%	2.09	1.25	2.19

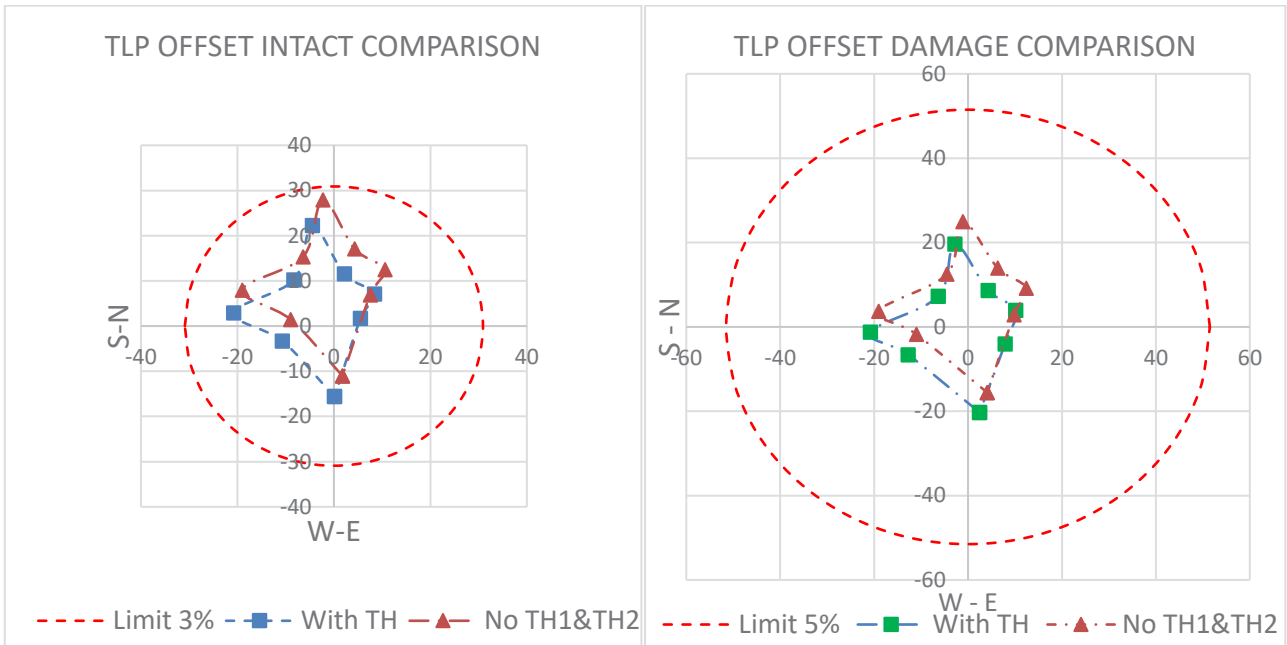
The worst results as show in table 2 above, is the maximum line tension occurs at line **D4** with **50.5%** MBS for damaged (1-line failure) condition.

This worst case occurs when the system takes an environmental force from north direction. All mooring lines tension safety factor are satisfied with the new lines.

### 3.1.2 TLP Offset and Clearance

We compared the TLP offset performances due to impact of the mooring lines and the separation distance between

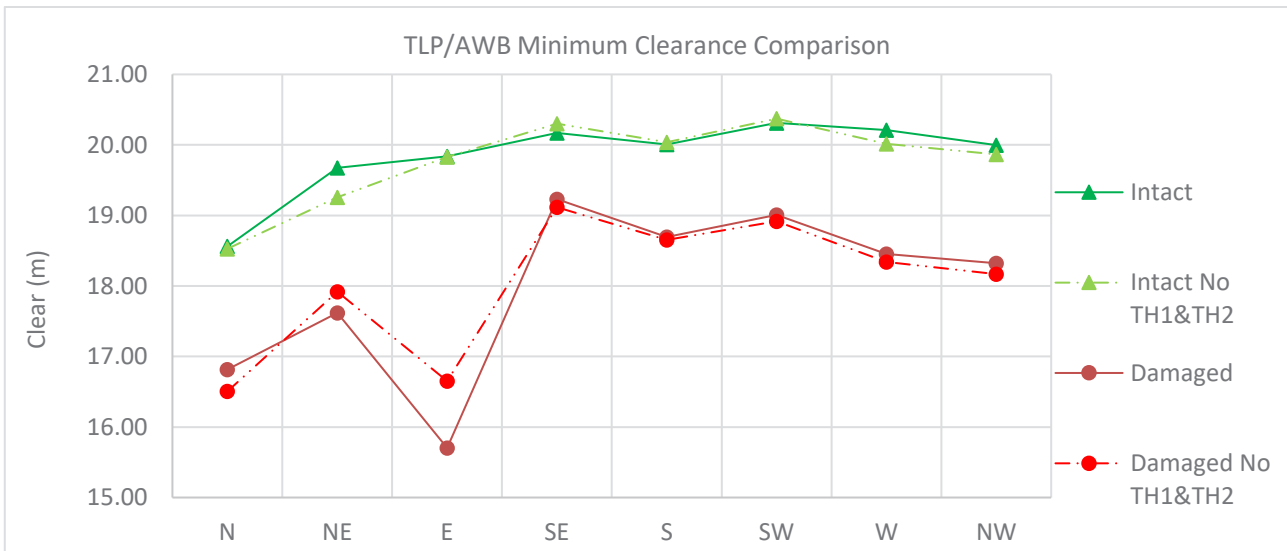
vessel and TLP. The offset for intact and damaged condition as shown in Fig. 9 below.



**Fig. 9.** TLP offsets comparison for Intact and Damaged condition

The maximum TLP offset occurs in the 100 YRP conditions from South, with and without TH lines where the offset reach 28m to North. This number almost exceeding the acceptance criteria (3% limit) 30 m for intact condition.

The minimum clearance comparison for both intact and damaged condition shown in Fig.10 below. The analysis asses the minimum separation distance between vessel surfaces during time simulation.



**Fig. 10.** AWB/TLP Clearance results comparison

Minimum clearance occurs when TH lines is included during damaged condition, the minimum separation distance recorded at 15.7 m when system took an environmental force coming from East direction. Although this result still satisfied the API acceptance criteria 10m. The effect of the TH lines on the TLP offset is practically quasi – static and the TLP may therefore

operate with the AWB connected and with a watch to the offset in case of strong southerly current. From the tension results, TLP offset and clearance results, we found that there is no significant effect of the TH1 & TH2 lines for the mooring lines system. Therefore, we can ignore the option to replace or repair those lines. However, the minor change of the vessel’s mooring properties is needed

to improve line tension capacity. The maximum line tension occurred in line D4 for damaged condition in case of strong northerly environmental forces.

### 3.2 Reliability analysis Results

In this study, we performed 50 Monte Carlo simulation to assess probability of failure from line D4 as representation from the recommended design. The wave height variable acted as load parameter while Minimum Breaking Load (MBL) of the line acted as resistance parameter with no safety factor applied (safety factor = 1).

50 random northerly waves variable were developed using Kolmogorov – Smirnov (K – S) test [5]. The K – S test compares the observed cumulative frequency and the CDF of an assumed theoretical distribution. The analysis conducted using ORCAFLEX simulation for dynamic mooring analysis in damaged condition without TH1&TH2 lines. The failure criteria meet simply when the load is greater than line D4 capacity (%MBS > 1).

From the observed data (see Fig.11), normal distribution is closest (see Table.3) compared to data with level of significance factor 15%.

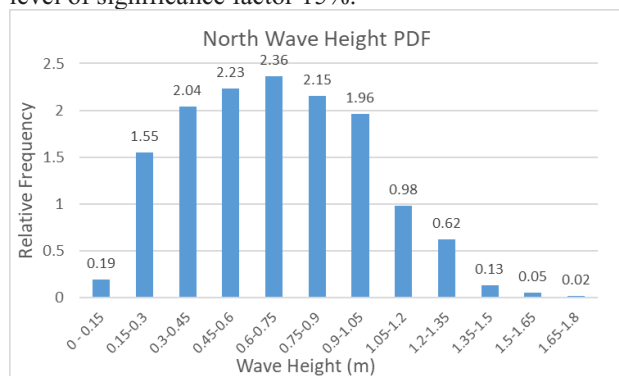


Fig. 11. North wave height observed data PDF

The observed wave height data is a height (H) and periode (T) data with relation as shown in this formula.

$$T = 1.9308H + 2.9198 \quad (5)$$

Table 4. K – S test result distribution

Distribution	Kolmogorov Smirnov	
	D <sub>N</sub>	Rank
Normal	0.1137	1
Rayleigh	0.11524	2
Gumbel Max	0.14362	3
Lognormal	0.16258	4

The K – S test given the two parameters for normal distribution as mean ( $\mu_E$ ) = 0.684 m, and standard deviation ( $\sigma_E$ )=0.313 m. From this distribution parameter, we generated 50 random northerly wave height data (see Fig.13) to run on the simulation using MATLAB application.

Mooring analysis using ORCAFLEX simulation generated 50 simulations with 50 generated wave height data as load parameter. The results will be 50 MBS (%) data of line D4 from the recommended design.

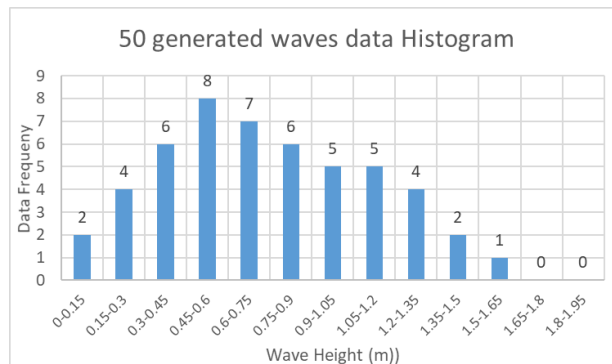


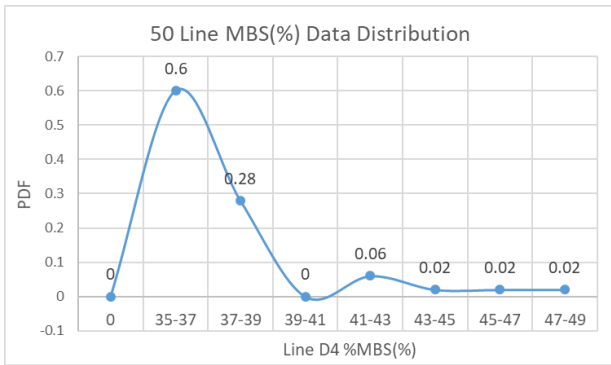
Fig. 12. Generated waves data for simulation

From the simulation results (see Table.4), it is found that none of the trials resulted in failure of the line, giving the corresponding probability of failure to be zero. This would happen when the number of simulation (N) is relatively small (below 100 simulation). The maximum MBS result occurs in trial no.39 with 48% MBS.

As there is no failure occur in the simulations, we still managed to calculate the probability of failure by analyse the PDF of MBS results (see Fig). The results data is closest (see table) to lognormal distribution based on the K-S test with level of significance factor reach 15%.

Table 3. 50-simulation results

No	H(m)	T(s)	Steady State			No	H(m)	T(s)	Steady State		
			D4 Tension (kN)	D4 Tension (t)	D4 %MBS				D4 Tension (kN)	D4 Tension (t)	D4 %MBS
1	0.987	4.825	648.8	66.1	38%	26	1.073	4.992	659.8	67.3	39%
2	0.694	4.259	626.9	63.9	37%	27	0.585	4.050	619.8	63.2	36%
3	1.107	5.056	664.5	67.7	39%	28	0.223	3.350	608.1	62.0	36%
4	0.202	3.310	608.3	62.0	36%	29	0.409	3.709	612.4	62.4	36%
5	0.759	4.386	630.5	64.3	37%	30	0.396	3.683	612.2	62.4	36%
6	0.297	3.494	610.3	62.2	36%	31	1.408	5.638	728.3	74.2	43%
7	0.878	4.614	638.5	65.1	37%	32	0.868	4.596	637.8	65.0	37%
8	1.092	5.029	662.4	67.5	39%	33	0.587	4.053	616.9	62.9	36%
9	1.004	4.859	650.8	66.3	38%	34	0.361	3.617	611.7	62.4	36%
10	1.380	5.584	720.7	73.5	42%	35	0.612	4.100	621.6	63.4	36%
11	0.897	4.652	640.0	65.2	37%	36	0.791	4.447	632.4	64.5	37%
12	0.687	4.246	626.5	63.9	37%	37	1.460	5.739	742.9	75.7	44%
13	0.789	4.442	632.3	64.5	37%	38	0.402	3.695	612.3	62.4	36%
14	0.513	3.910	614.8	62.7	36%	39	1.613	6.034	817.8	83.4	48%
15	0.168	3.243	608.8	62.1	36%	40	0.680	4.234	626.1	63.8	37%
16	0.963	4.780	646.2	65.9	38%	41	0.059	3.033	604.7	61.6	35%
17	0.525	3.934	615.5	62.7	36%	42	0.406	3.704	612.3	62.4	36%
18	0.581	4.041	619.5	63.1	36%	43	0.553	3.987	617.4	62.9	36%
19	0.737	4.342	629.3	64.2	37%	44	0.901	4.660	640.4	65.3	38%
20	1.478	5.773	784.5	80.0	46%	45	0.633	4.142	623.1	63.5	37%
21	1.401	5.626	726.6	74.1	43%	46	0.716	4.302	628.2	64.0	37%
22	0.272	3.444	609.2	62.1	36%	47	0.678	4.230	626.0	63.8	37%
23	0.536	3.954	616.2	62.8	36%	48	0.384	3.661	612.0	62.4	36%
24	0.993	4.837	649.5	66.2	38%	49	1.051	4.949	656.8	67.0	38%
25	0.036	2.989	595.7	60.7	35%	50	0.570	4.020	618.7	63.1	36%



**Fig. 13.** Line MBS (%) PDF

Lognormal distribution can be used to theoretically represent line D4 tension MBS data with parameter:

- Mean  $\lambda_{MBS} = -0.98095$
- Standar Deviation  $\xi_{MBS} = 0.06684$

**Table 5.** K-S Test on MBS results

#	Distribution	Kolmogorov Smirnov	
		Statistic	Rank
1	Lognormal	0.21668	1
2	Normal	0.22981	2
4	Weibull	0.25255	3
3	Rayleigh	0.49198	4

From the above PDF, probability of failure ( $P_f$ ) of D4 as representative from the recommended mooring design can be calculated using the curve area where  $1 \leq \%MBS < \infty$ . The area will be calculated using following formulae.

$$P(a < X \leq b) = \frac{1}{\sqrt{2\pi}} \int_{\left(\frac{\ln a - \lambda_x}{\xi_x}\right)}^{\left(\frac{\ln b - \lambda_x}{\xi_x}\right)} \exp\left[-\frac{1}{2}s^2\right] ds$$

$$= \Phi\left(\frac{\ln b - \lambda_x}{\xi_x}\right) - \Phi\left(\frac{\ln a - \lambda_x}{\xi_x}\right) \quad (6)$$

$$P(\text{success}) = p_s = 1 - p_f \quad (7)$$

Then we calculate the probability of failure on line D4 as shown in calculation below:

$$p_f = P(\%MBS \geq 1)$$

$$p_f = 1 - \left[ \Phi\left(\frac{\ln 1 - \lambda_{MBS}}{\xi_{MBS}}\right) - \Phi\left(\frac{\ln(-\infty) - \lambda_{MBS}}{\xi_{MBS}}\right) \right]$$

$$p_f = 1 - \left[ \Phi\left(\frac{\ln 1 - \lambda_{MBS}}{\xi_{MBS}}\right) - \Phi(-\infty) \right]$$

$$p_f = 1 - \left[ \Phi\left(\frac{\ln 1 - (-0.98095)}{0.06684}\right) - 0 \right]$$

$$p_f = 1 - \Phi(14.676)$$

Using the equation (3), the reliability index is calculated:

$$\beta = \Phi^{-1}(\Phi(14.676))$$

$$\beta = 14.676$$

The reliability index shows a very large value in offshore platforms reliability criteria [10] with very small probability of failure (below  $10^{-7}$ ) on line D4 for damaged condition without TH1 & TH2 lines.

## 4 Conclusions

To verify the mooring performances of an Accommodation Working Barge on Tension Leg Platform in Makassar Strait, this study has found that.

- 1) For the mooring configuration, all safety factors are verified with and without TH lines with recommendation to change the AWB mooring lines connected to the TLP with new IWRC 54mm wires with MBL 174 tonnes from EEIPS 38 mm wires with MBL 90 tonnes. This change aimed to increase break capacity when the storm 100YRP occurs. It is advised to set the vessel wire loose (about 2m) when the storm occurs.
- 2) In the 100 YRP storm conditions, the line tension limit, TLP offset, and clearance between two vessels satisfied all the API criteria.
- 3) The maximum tension limit occurs in line D4 (87.9 tonnes / 50.5%MBS) for strong northerly environmental forces during 1-line failure condition. The maximum TLP offset is 27.89 m in case of strong southerly current, and the minimum clearance meet API criteria (>10m) which is 15.7 m when easterly environmental forces occur.
- 4) Based on the mooring analysis, the effect of the TH lines on the system performances is practically non-significant. Therefore, the recommended design should proceed without TH1&TH2 lines.
- 5) This study assesses reliability index of the recommended design using Monte Carlo simulation. The system has very high reliability index (14.68) with probability of failure below  $10^{-7}$ .

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