2301-9069 (e)
1829-8370 (p)

KAPAL

Jurnal Ilmu Pengetahuan dan Teknologi Kelautan

journal homepage : http://ejournal.undip.ac.id/index.php/kapal

An Analysis on the Spread Mooring of the Belida FSO Induced by Squall Loads

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Article Info

Keywords:
Squall,
FSO,
Spread Mooring,
Mooring Tension,
Offset

Article history:
Received: 25/12/19
Last revised: 31/01/20
Accepted: 31/01/20
Available online: 29/02/20

DOI:
https://doi.org/10.14710/kapal.v17i1.27554

Abstract

Squall is the occurrence of a sudden sharp increase in wind speed, thus amplifies sea environmental loads. In the South of Natuna Sea, squall can reach an intensity of up to 50 m/s or close to 100 knots. In this water, the Belida FSO operates at a water depth of 77.0 m, tethered to the seabed by a spread mooring system. Squall's impacts on the FSO mooring system has been examined by implementing time-domain simulations accommodated in a numerical model based on the 3-D wave diffraction theory. The simulations were performed by varying the squall duration of escalation, i.e. 2.5, 5.0, and 10.0 minutes, for the load cases of 1-year extreme operational and 100-year extreme survival conditions propagating at 0°, 45°, 90°, 135°, 180°. The three squall durations of escalation substantially increase the significant wave height Hs by averagely 60%, 50% and 34%, respectively. The largest of the maximum mooring tension due to the sea load directions is found to be brought about the 45° load when magnified by the squall with a 2.5-minute duration of escalation. In this respect the largest intensities of the operational and survival tension loads may reach some 2,027 kN and 3,318 kN, respectively, which are eventually far below the MBL of 7,685 kN. The largest x-axis offsets in operational and survival conditions are 3.94 m and 10.21 m, respectively. Whereas the largest y-axis offsets for operational and survival loads are found to be 13.31 m and 15.48 m. These y-axis offset intensities are larger than the limiting criteria, i.e. 15% of the water depth or 11.55 m.

1. Introduction

Floating Storage and Offloading (FSO) is a vessel that functions as a floating oil storage terminal as well as to transfer the product of an offshore field. In its operation, the FSO should be maintained to have the dynamic and stationary stability in its position, by mooring to the seabed. One type of system that is widely used is the spread mooring. According to API [1], spread mooring is a mooring system in which a mooring line is attached to each end corner of the floating structure, thus limiting the floating structure not to move freely. In a spread mooring design, the conventional approach is, in general, only be based on the condition of the marine environment with a certain degree of severity, without any fluctuations. However, in reality, the marine environment load often experiences unexpected severe changes.

One of the phenomena in the sea that is classified as an unexpected event leads to extreme load magnification is known as squall. According to DNV [2], squall is an event of a sudden and sharp wind speed increase, followed by a sudden change in wind direction, which then decreases the speed of the wind. Squall events generally occur within a period for approximately 1 hour, but the initial escalation typically takes a short time, in several minutes.

Duggal et al. [3] have researched the effects of squall off the coast of West Africa, by observing their impact on the environmental loads and the shifting or offset of the floating structures based on extreme design conditions. Furthermore, Liu et al. [4] have shown the characteristics of the squall, which have a significant impact on the response of mooring systems and floating structures by reviewing the variables of peak wind speed, wind duration, and the projected surface area of the affected floating structure. This finding is also supported by the statement of Oberlies et al. [5], which showed that the direction of the ship heading relative to the squall direction had a real effect on the magnitude of the vessel offset and the mooring tension.

The current paper is presented to describe the results of a study with the case of the Belida FSO tethered by the spread mooring system in the South Natuna Sea at a water depth of 77.0 m, where squall phenomena occur quite frequently. The study is conducted to determine the impact on the FSO motions and mooring responses that took place due to the increase in environmental loads by squall, when compared with extreme environmental conditions according to the conventional design. The analysis is yielded from the results of time-domain simulations accommodated in a numerical model based on a

3-D wave diffraction theory. The squall effect on the environmental load has been included as a transient load from the wind speed escalation in a short fluctuation [6], which is varied within 2.5, 5.0, and 10.0 minutes. This is further induced onto the moored FSO and manifests in the FSO motions, mooring tensions, and FSO offsets.

The results of the current study offer some benefits in conjunction with the moored floating offshore systems. Firstly, give a better understanding of the phenomenon of squall and modeling of its effects on the systems. Secondly, provide a recommendation for the new design of the systems to be operated in the waters where squalls are frequently occurring. Thirdly, present an analysis reference to establish mitigation for the systems already in operation but prone to the risk of squalls.

2. Methods

This study is commenced with the collection of literature, which will be used as a reference, taken from textbooks, journals, theses, dissertations, codes, standards, and rules. The kinds of literature are mainly selected, which relates to the basic theory of hydrodynamics, spread mooring system analysis, wind squall analysis, and vessel responses to environmental conditions affected by squalls. This step is followed by data collection, modeling the FSO hull and mooring system, analysis of squall effects on environmental data. The next stage is an analysis of the FSO mooring tension and offset by considering the results of time-domain simulation accommodated in a numerical model based on the 3-D wave diffraction theory. The steps mentioned above are depicted in the flowchart diagram in Figure 1.

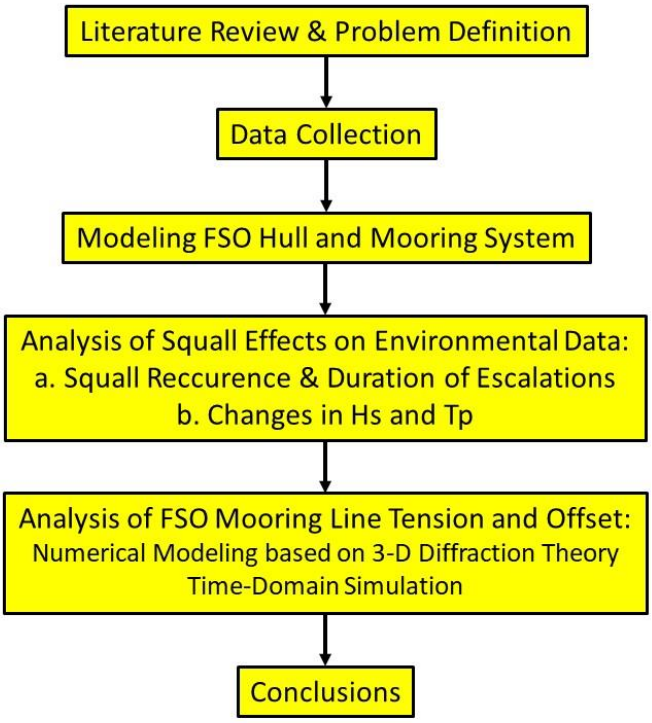


Figure 1. Flowchart Diagram of the Methodology for the Current Study

2.1. Data Collection

The data so required in this study includes the main dimensions of the Belida FSO, specifications of the mooring lines, environmental data for design conditions, and the recorded squall event data. Table 1 and Table 2, respectively, show the principal dimensions of the Belida FSO and the mooring data. Whereas environmental data for design conditions at South Natuna Sea comprise the extreme operational data with a 1-year recurrence and the extreme survival data with a 100-year recurrence, are as shown in Table 3, Table 4, and Table 5, respectively, for wind, wave, and current.

Table 1. Main Dimensions of the Belida FSO

Parameter	Unit	Value
LOA (length over all)	m	244.60
LPP (lenght beetween Perpendicular)	m	233.00
B (Breadth)	m	42.20
H (Height)	m	22.20
T (Draught)	m	14.90
KG (Keel to Gravity)	m	13.71
Δ (Displacement)	ton	128,588.60
K_{xx} (roll radius gyration)	m	17.40
K_{yy} (pitch radius gyration)	m	69.73
K_{zz} (yaw radius gyration)	m	69.73

Table 2. Data of Mooring Lines

Parameter	Unit	Value
Nominal Diameter	mm	87.00
Type/Grade	-	Studless/R4
Number of mooring lines	-	8
Payout length	m	914.00
Approximate horizontal length	m	900.00
Pretension	kN	768.20
Minimum Breaking Load (MBL)	ton	783.35

Table 3. Recurrence Data on the Wind Speed (V_w in m/s)

Return Period	Wind Direction				
	0°	45°	90°	135°	180°
1-year	11.0	11.0	8.0	9.0	15.0
100-year	14.0	14.0	11.0	12.0	20.0

Table 4. Recurrence Data on The Significant Wave Height *Hs* (m) and Wave Peak Period *Tp* (sec)

Direct.	Hs (m)		Tp (s)	
	1-year	100-year	1-year	100-year
0°	1.7	2.3	8.4	8.7
45°	1.7	2.3	8.4	8.7
90°	1.5	2.0	8.3	8.6
135°	1.7	2.3	8.4	8.7
180°	3.7	5.0	9.6	10.3

Table 5. Recurrence Data on the Current Velocity (V_c in m/s)

Direction	Water Depth					
	76.81 m		46.81 m		3 m	
	1-yr	100-yr	1-yr	100-yr	1-yr	100-yr
0°	0.62	0.89	0.5	0.67	0.38	0.46
45°	0.51	0.74	0.41	0.56	0.32	0.38
90°	0.51	0.74	0.41	0.56	0.32	0.38
135°	0.66	0.95	0.53	0.71	0.41	0.45
180°	0.74	1.05	0.59	0.78	0.45	0.55

2.2. Modeling the Belida FSO Hull and Mooring System

The modeling of the Belida FSO is performed utilizing MAXSURF Modeller and MOSES software. In the FSO modeling, both using MAXSURF and MOSES, it should consider the validity of the parameter data obtained. According to ABS [7], the data to be confirmed is from its hydrostatic parameters, i.e., the error rate should not exceed 2.0% if compared to the original data. After the Belida FSO hull is modeled, the mooring system modeling is then performed. In this case, a spread mooring system has been chosen with eight mooring lines (L1 up to L8) having a catenary configuration, as illustrated in Figure 2.

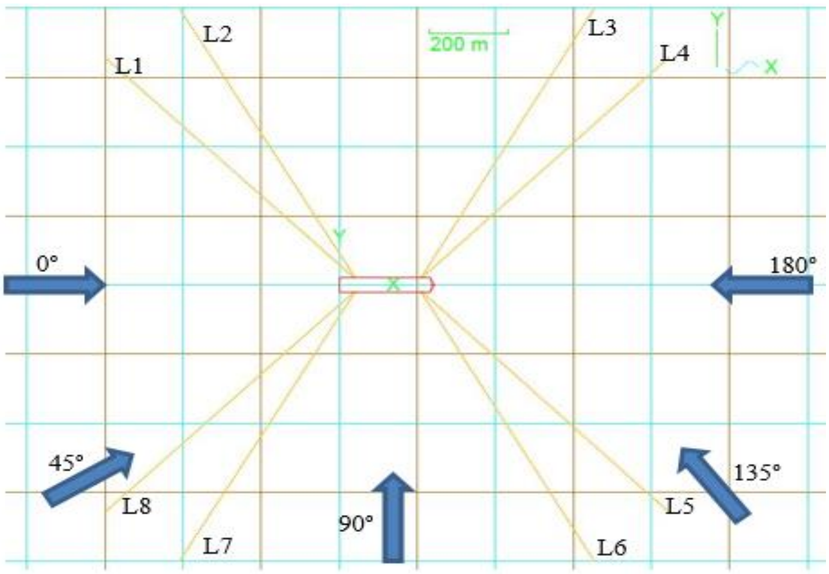


Figure 2. Modeling of The Spread Mooring System and The Scenario Of Environmental Load Directions

2.3. Analysis on the Squall Effect on the Environmental Data

2.3.1. Squall Recurrence

The squall data for the South Natuna Sea that has been obtained is in the form of squall wind speed records for three years. The data is then processed by applying the Weibull distribution, with a form parameter value $k = 2.0$ [8,9], to determine the recurrence period of squall, as contained in Table 6. After the squall wind speed recurrence is obtained, the next step is to compose the tendency curve of the squall wind speed escalation in a time-domain basis [9].

Table 6. the Squall Recurrence and Intensities in South Natuna Sea

Return Period	Squall Wind Speed (m/s)
1-year	20.0
100-year	33.0

2.3.2. Prediction of Wave Heights and Periods due to Squall

Environmental loads without squall are simulated by referring to the data from Tables 3, 4, and 5, to obtain the time history of random sea conditions. This step is carried out by regenerating from a wave spectra, specifically the JONSWAP spectra with peakedness parameter γ=2.5, which is considered appropriate to model the random sea waves in Natuna Sea [10]. Next, the intensities of the elevation in the time history are magnified by taking into account the dynamic amplification factor (DAF), to simulate the effect of the squall. DAF was obtained from the equation of the squall wind speed escalation curve for three variations of the duration of escalation, which are 2.5, 5.0, and 10.0 minutes. The DAF is principally established by considering that the escalation is occurring exponentially as a function of time elapsed [11,12]. By accounting for the escalation equation in the computation yields a new time history of random sea elevation that reflects the effect of the squall loads.

From the new elevation obtained, then the elevation in the time-domain is transformed into a wave energy spectrum in the frequency-domain. The transformation process is accomplished by making use of the Fast Fourier Transform (FFT) algorithm, with the help of MatLab software. Furthermore, computation is conducted based on the wave energy spectrum curve to produce new *Hs* and *Tp* due to squall loads [10].

2.4. Analysis of FSO Mooring Line Tension and Offset

Analysis to determine the structural responses in the form of tension in the mooring system and shifting motions or offsets that arise on the Belida FSO is carried out in two stages. The first stage is imposing excitation of the environmental loads for the extreme operational and survival conditions, correspondingly related to 1-year and 100-year return periods. The second stage is to provide excitation of environmental loads that have been magnified by the squall, with the period of escalations of 2.5, 5.0, and 10.0 minutes. Besides, for loading with squall conditions having the 10 minutes of escalation, the *Tp* values are varied according to DNV-OS-E301 [13], i.e., for the South Natuna Sea area, which is included in the South China Sea region. Specifically for this region, *Tp* = 11.1 secs is taken when a typhoon is not present, and *Tp* = 15.1 secs is considered when typhoon occurs. Because the interval of the two *Tp* is rather large, two additional variations of *Tp* values have been given, namely 12.5 secs and 13.5 secs. The next step is to compare the mooring tensions and the FSO offsets under the loading conditions considered in this study.

Analysis of mooring line tensions and FSO offsets is carried out regarding the following dynamic formulation of floating body motions [14,15]:

$$\sum_{j=1}^{6}[-\omega^2(\mathbf{M}_{jk}+\mathbf{A}_{jk})-i\omega\mathbf{B}_{jk}+\mathbf{C}_{jk}+\mathbf{C}_{jk}^{m}]\zeta_j=\mathbf{F}_j \tag{1}$$

where

j,k = 1, 2, 3 for translational motions in the direction of *x*-, *y*-, and *z*-axis, namely surge, sway, and heave, while 4, 5, 6 for rotational motions about the *x*-, *y*-, and *z*-axis, namely roll, pitch, and yaw;

= wave frequency;

$\mathbf{M}_{jk}$ = matrix of floating structure mass and mass moment of inertia about the reference axes;

$\mathbf{A}_{jk}$ = matrix of added mass and added mass moment of inertia in accordance with the floating structure mode of motions;

$\mathbf{B}_{jk}$ = matrix of hydrodynamics damping in accordance with the floating structure mode of motions;

$\mathbf{C}_{jk}$ = matrix of floating structure hydrostatic stiffness;

ζ_j = amplitude of the j^{th} floating structure mode of motion;

$\mathbf{F}_j$ = matrix of the j^{th} excitation force and moment, which contains of the following elements:

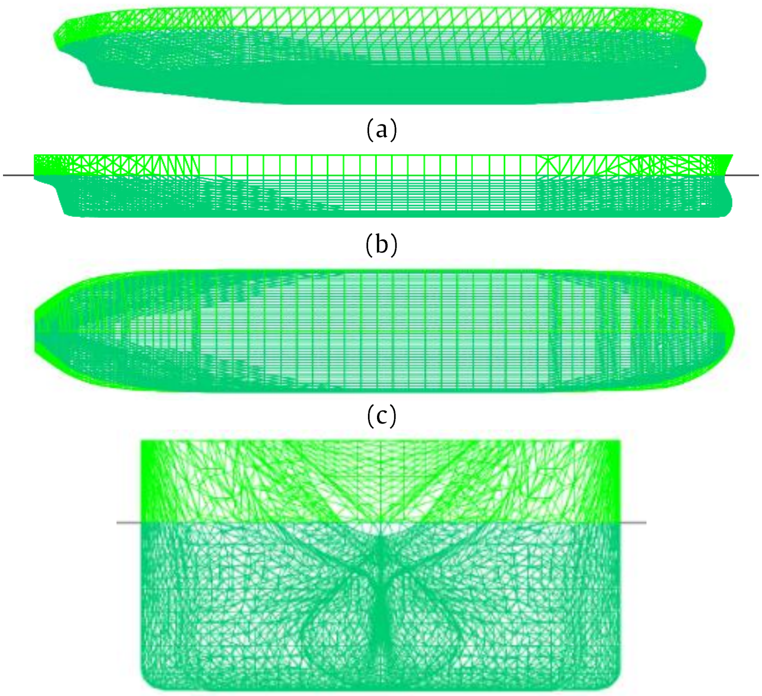
$$\mathbf{F}_j=\mathbf{F}_{j-wv}^{(1)}+\mathbf{F}_{j-wv}^{(2)}+\mathbf{F}_{j-c}+\mathbf{F}_{j-w}+\mathbf{F}_{j-m} \tag{2}$$

Variables in Eq. 2 represent matrices of the 1st-order wave excitation $\mathbf{F}_{j-wv}^{(1)}$, 2nd-order wave excitation $\mathbf{F}_{j-wv}^{(2)}$, current excitation $\mathbf{F}_{j-c}$, wind excitation $\mathbf{F}_{j-w}$, and excitation due to mooring system $\mathbf{F}_{j-m}$.

3. Results and Discussion

3.1. Modeling of the Belida FSO and Validation

At this stage, modeling is aimed at designing the FSO hull by referring to the main dimensions, as given in Table 1. Initial modeling is performed using MAXSURF software, taking the data of a tanker with a capacity of about 100,000 DWT, and processed to have dimensions of length over all, breadth, and deck height, correspondingly, 244.6 m, 42.2 m, and 22.2 m. The result of the MAXSURF model is then transferred to MOSES software and plotted, as shown in Figure 3.



(a)

(b)

(c)

(d)

Figure 3. Model of the Belida FSO Hull Yields by MOSES: a) Isometric View, b) Side View, c) Top View, and d) Front View

The result of the final modeling by MOSES is then validated. At the draft of 14.9 m, the vessel has a displacement of 128,561 tons. This value differs only about 0.02% in comparison to the original data of the Belida FSO, which is 128,589 tons. Other hydrostatic parameters have also been validated, and all of those have a discrepancy of no more than 2.0%. Therefore, the hull modeling essentially satisfies the validity criteria as required by ABS [7].

The hull model and the related data so obtained are further utilized as the input data to compute the FSO motions for the free-floating condition in frequency-domain, also employing MOSES. The corresponding output data covers the motion response amplitude operators (RAOs) in 6-DOF, as well as the 1st–order force and moment of excitation. These output data from MOSES are subsequently accounted for as the input data to run a time-domain simulation of FSO in moored conditions, according to Eq. 1, by implementing the OrcaFlex software.

3.2. Analysis of Environmental Data with Squall

As it has been addressed in the introduction, squall is the occasion of a sudden and sharp increase in wind speed. A number of researchers have proposed the modeling in which the sharp increase develops [16,17]. In general, previous investigations indicate that during a squall, wind speed will escalate exponentially in time. Referring to the squall data for the South Natuna Sea and previous investigations, the squall escalation pattern may be represented by the DAF equations, as listed in Table 7. The equation of squall escalation eventually is a function of time t in minutes and the associated coefficient. For the current study, the time t is varied in three different duration of escalations, i.e., 2.5, 5.0, and 10.0 minutes. The extremities of the environmental loads specify the associated coefficients to that duration of escalations, which is the 1-year recurrence of extreme operational and 100-year recurrence of extreme survival.

Table 7. Dynamic Amplification Factor to Simulate the Wind Speed Increase due to Squall

Condition		DAF
Squall t =2.5 mins	1-year	esc = exp (0.201 x t)
	100-year	esc = exp (0.234 x t)
Squall t = 5.0 mins	1- year	esc = exp (0.101 x t)
	100- year	esc = exp (0.117 x t)
Squall t = 10.0 mins	1- year	esc = exp (0.058 x t)
	100- year	esc = exp (0.067 x t)

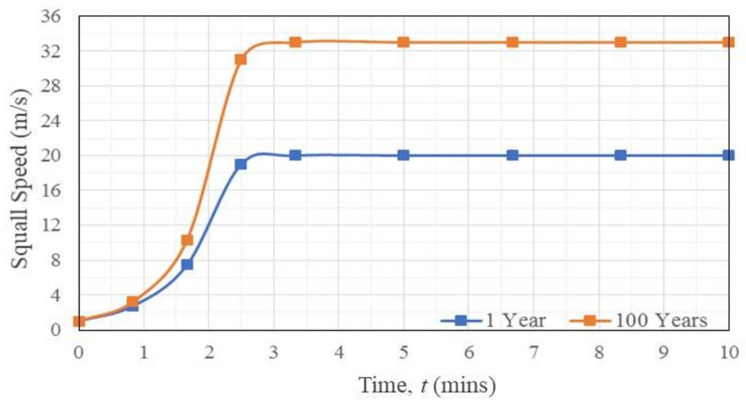


Figure 4. Curves of Wind Speed Increase due to Squall with 2.5 Minutes Duration of Escalation

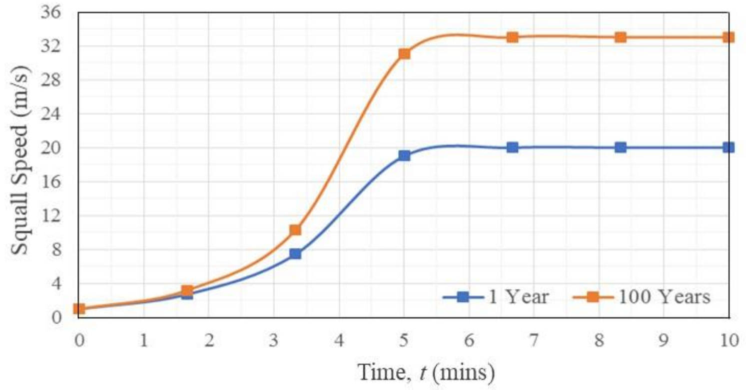


Figure 5. Curves of Wind Speed Increase due to Squall With 5.0 Minutes Duration of Escalation

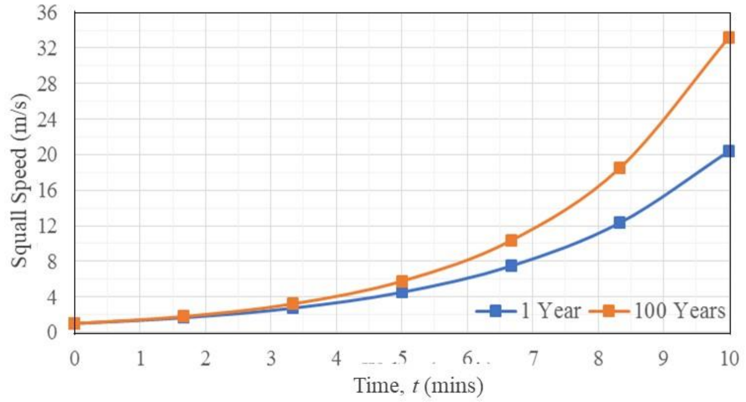


Figure 6. Curves of Wind Speed Increase due to Squall with 10.0 Minutes Duration of Escalation

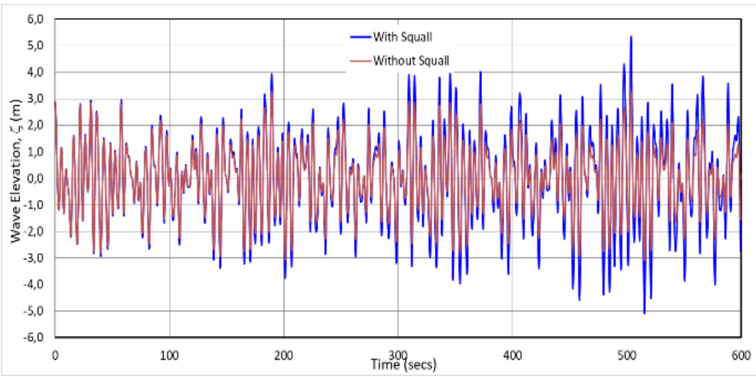


Figure 7. Effect of a Squall with 10-Minute Duration of Escalation on the Elevation of 100-Year Wave Recurrence With 180° Propagation

Referring to the DAF equations in Table 7 and the maximum squall speeds in Table 6, one may draw the curve of wind speed escalation for squall durations of 2.5, 5.0, and 10.0 minutes, combined with a 1-year and 100-year extreme conditions, as in Figures 4, 5, 6. In each of these figures, the wind speed curve for the severe 1-year recurrence will rise from a value of 0.0 m/s to a maximum of 20.0 m/s, while for the extreme 100-year recurrence will increase from 0.0 m/s to a maximum of 33.0 m/s, along with the squall duration of escalation. After the maximum speed is reached, the wind speed is assumed to have a constant value [3,4]. The effect of the squall on the change in wave elevation is then computed by accounting for the incremental values from the curve of wind speed escalation into the time history of random waves. For example, the computational results of a 10.0 minutes (600 secs) squall effect on a 100-year wave with a direction of 180°, are as shown in Figure 7. The red color curve exhibits the initial wave elevation before the squall takes place. The curve in blue color is the wave elevation after squall effect is imposed. It is obvious herein that wave elevation influenced by the squall is gradually increasing higher than the initial wave elevation.

3.2.1. The changing of *Hs* due to Squall

The process for obtaining values of significant wave heights of random waves under squall conditions, as explained previously, is using the FFT algorithm [10]. The input data required is the time history of random wave elevations, such as depicted in Figure 7. Such wave elevations are then processed to produce a wave energy spectra curve [18,19], as exemplified in Figure 8.

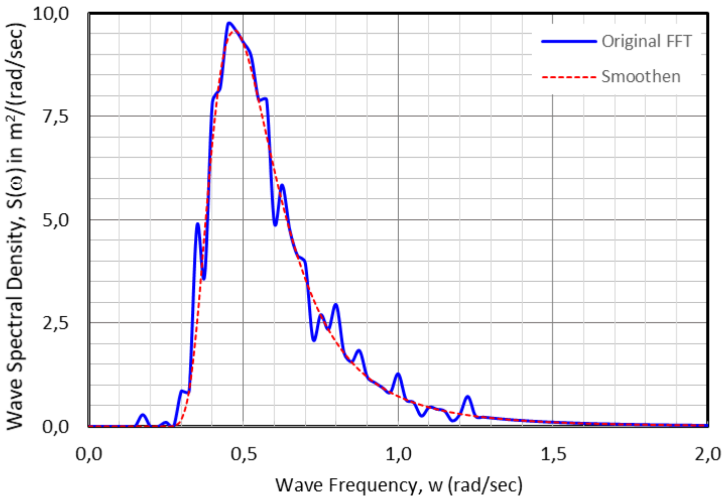


Figure 8. Wave Energy Spectra Resulted from FFT of The 100-Year Random Wave Propagating 180° Affected By A 10-Minute Squall

From a wave energy spectra curve, as in Figure 8, significant wave height Hs can be derived, by firstly computing the area under the spectra curve, m_0. Considering the value of m_0 the Hs is then obtained from the following equation

$$H_S = 4.0\sqrt{m_0}\,(\mathrm{m}) \tag{3}$$

The results of computation based on overall wave data with various directions and extremity levels, as given in Table 4, after being subjected to the squall effect, yield the values as listed in Table 8. From this table, it can be seen that a squall with a shorter escalation to reach the maximum wind speed will produce a more considerable increase in the value of *Hs*. On average, a squall with a duration of escalation of 2.5, 5.0, and 10.0 minutes will increase *Hs* by about 60%, 50% and 34%, respectively.

Table 8. Values of *Hs* for Sea Environment without and with Squall Effects

Direction	**Return Period**	**Hs (m)**			
		No Squall	**Squall 2.5 min**	**Squall 5 min**	**Squall 10 min**
0°	1-year	1.7	2.7	2.5	2.2
	100-year	2.3	3.7	3.5	3.2
45°	1-year	1.7	2.7	2.5	2.2
	100-year	2.3	3.7	3.5	3.2
90°	1-year	1.5	2.4	2.2	1.9
	100-year	2.0	3.2	3.0	2.7
135°	1-year	1.7	2.7	2.5	2.2
	100-year	2.3	3.7	3.5	3.2
180°	1-year	3.7	6.0	5.7	5.0
	100-year	5.0	8.1	7.7	7.0

3.2.2. The Changing of *Tp* due to Squall

The computation of the wave peak period Tp is carried out by also referring to the wave energy spectra curve, such as in Figure 8. However, in this case, it is necessary first to determine the 2nd and 4th moments of the area under the wave spectra curve, respectively, m_2 and m_4 [10]. Next, the Tp is computed by the equation

$$T_P = 2\pi\sqrt{m_2/m_4}\ \text{(secs)} \tag{4}$$

Analysis of all of the observed wave data has been conducted. The results of which are as brought together in Table 9. From this table, it can be seen that the effect of the squall on the alteration of Tp is trivial. Generally, either the squall with the duration of escalation 2.5, 5.0, or 10.0 minutes will only increase the Tp in the order of only 1.2% or less.

Table 9. Values of *Tp* for Sea Environment without and with Squall Effects

Direction	Return Period	Tp (m)			
		No Squall	Squall 2.5 min	Squall 5 min	Squall 10 min
0°	1-year	8.4	8.5	8.5	8.5
	100-year	8.7	8.8	8.8	8.8
45°	1-year	8.4	8.5	8.5	8.5
	100-year	8.7	8.8	8.8	8.8
90°	1-year	8.3	8.4	8.4	8.4
	100-year	8.6	8.6	8.6	8.6
135°	1-year	8.4	8.5	8.5	8.5
	100-year	8.7	8.8	8.8	8.8
180°	1-year	9.6	9.8	9.8	9.8
	100-year	10.3	10.4	10.4	10.3

3.3. Results of Analysis on Mooring Line Tensions

The analysis at this stage is carried out based on the results of the time-domain simulation of the environmental load excitation in the collinear combinations of wind, current, and wave advancing in 5 directions of propagation to the Belida FSO in a tethered state. The primary input data of environmental loads for simulation are varied for operational and survival extremes, both in an environment without squall and taking into account the squall effects of 2.5, 5.0, and 10 minutes duration of escalation, as summarized in Table 3 to 8. In addition, the simulation also takes into account variations in *Tp* as from Table 9 and considers the influence of typhoons as discussed in sub-section 2.4.

All simulations are carried out according to the codes and standards, i.e., over 30 minutes or 1,800 seconds [13,20,21]. Results of the simulation in terms of the mooring tension intensities are presented in Figures 9, 10, 11, 12, 13. Those figures are taking into account environmental loads without squall and with the squall of 10.0 minutes duration of escalation, both for extreme operational and survival conditions as a function of loading propagation.

Observing the curves in those figures, which are maximum tension brought about the load directions of 0°, 45°, 90°, 135°, and 180°, respectively, are found to be on the lines L1 and L8, L8, L6 and L7, L5, as well as L4 and L5. Considering that the environmental loads are random in nature, it should then be apprehended that the maximum tensions on any two symmetrical mooring lines, such as L1 and L8 due to 0° advancing load, actually are not the same. None the less, the tension values are a quite close one to another.

From all the loading directions reviewed, it eventually reveals that the largest among the maximum tensions is found to be when the environmental loading is affected by the squall. Table 10 is the summary of the largest among maximum tensions in each direction of loading for a squall with a duration of escalation of 10.0 minutes and variations in *Tp*. It is interesting to note that the most massive tension for the operational condition occurs on L6 and L7 when excited by the 90° advancing environmental load with *Tp* = 12.5 secs. For the case of survival condition, the most massive tension is experienced by L8 owing to the 45° load with *Tp* = 11.1 secs.

The subsequent computation process has been carried out for the other two squall durations of escalation, which are 2.5 and 5.0 minutes, also for the five directions of the environmental load as done in the case of squall with a 10-minute duration of escalation. The computational results of the maximum tension values for environmental loads without and with variations of three squall durations of escalation, combined with five loading directions, both for operational and survival conditions, are then summarized into one table for comparison purposes, as presented in Table 11.

Results in Table 11 indicate the largest of the maximum tensions are eventually owing to the environmental loads under the influence of a 2.5-minute squall, for all load directions. Overall, either for the case of extreme operational or survival conditions, the largest of the maximum tensions are found to be caused by the loads advancing 45° reaching, respectively, as much as 2,027.4 kN and 3,317.7 kN, take place on mooring line L8. Those most considerable tensions notably are still far below the maximum breaking load (MBL) of the mooring line, as listed in Table 2, which is 783.35 tons or 7,684.66 kN.

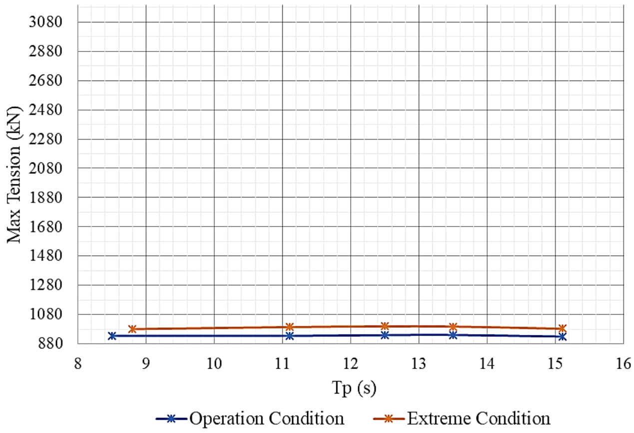


Figure 9. Curves of maximum tension (L1 & L8) due to a 10-minute squall with 0° direction

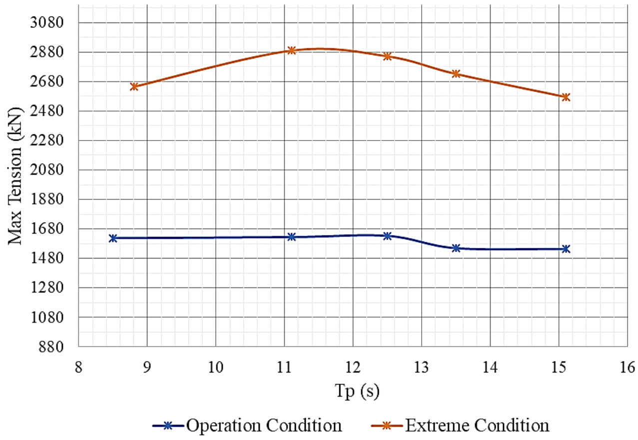


Figure 10. Curves of maximum tension (L8) due to a 10-minute squall with 45° direction

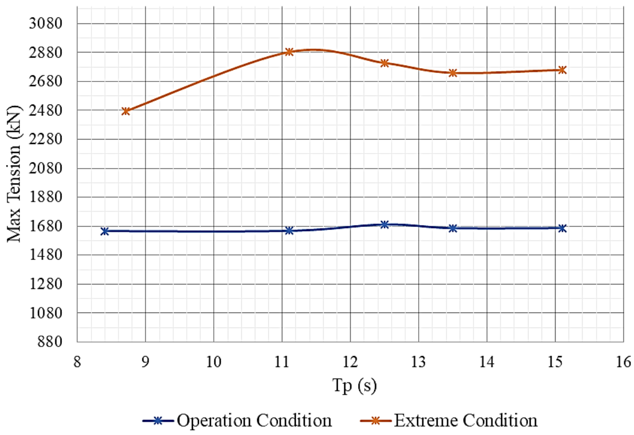


Figure 11. Curves of maximum tension (L6 & L8) due to a 10-minute squall with 90° direction

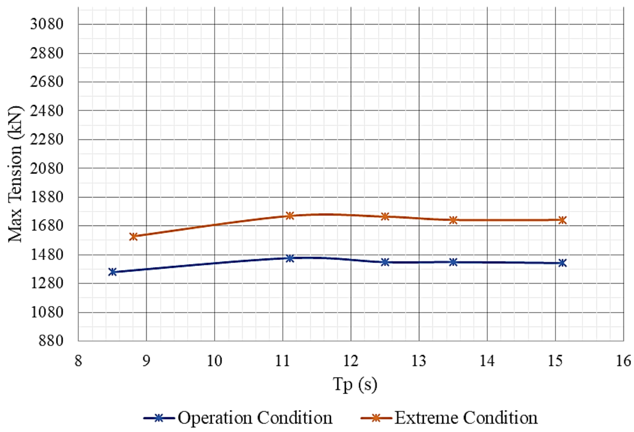


Figure 12. Curves of maximum tension (L5) due to a 10-minute squall with 135° direction

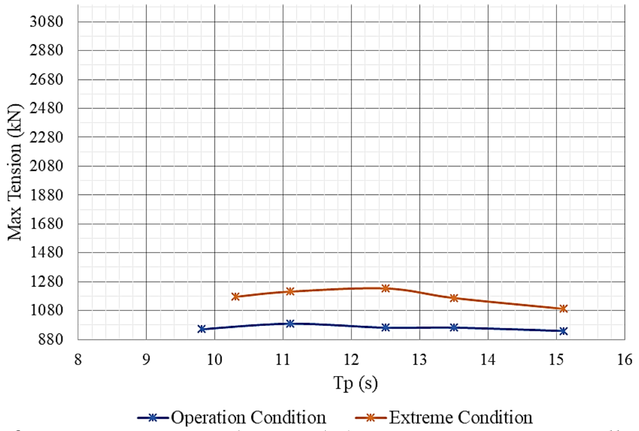


Figure 13. Curves of maximum tension (L4 & L5) due to a 10-minute squall with 180° direction

Table 10. the Largest of Maximum Tensions (kN) for Each Load Direction with a 10-Minute Squall

Direction	**Operational Condition (1-year)**	**Max Tension (kN)**	**Survival Condition (100-year)**	**Max Tension (kN)**	**Line**
0°	Squall Tp = 13.5 s	940.0	Squall Tp = 12.5 s	999.0	1 & 8
45°	Squall Tp = 12.5 s	1634.0	Squall Tp = 11.1 s	2890.0	8
90°	Squall Tp = 12.5 s	1692.0	Squall Tp = 11.1 s	2883.0	6 & 7
135°	Squall Tp = 11.1 s	1457.0	Squall Tp = 11.1 s	1750.0	5
180°	Squall Tp = 11.1 s	989.0	Squall Tp = 12.5 s	1233.0	4 & 5

Table 11. Maximum Tension (kN) as a Function of Squall Duration and Environmental Load Direction

Operational Condition (1-year)					
	Direction				
	0°	45°	90°	135°	180°
No Squall	913.5	1288.6	1304.0	1089.6	895.0
Squall 2.5 mins	***940.0***	***2027.4***	***2000.2***	***1556.7***	***1080.3***
Squall 5.0 mins	936.0	1842.9	1809.2	1455.6	1060.9
Squall 10.0 mins	937.1	1634.0	1692.0	1457.0	989.0
Survival Condition (100-year)					
	Direction				
	0°	45°	90°	135°	180°
No Squall	913.5	1288.6	1304.0	1089.6	895.0
Squall 2.5 mins	***1003.7***	***3317.7***	***3268.9***	***2281.2***	***1303.9***
Squall 5.0 mins	997.5	3079.0	3023.3	2130.9	1257.6
Squall 10.0 mins	999.0	2890.0	2883.0	1750.0	1233.0

3.4. Results of Analysis on FSO Offsets

In this sub-section, the results of the analysis on offset intensities that occur on the Belida FSO due to environmental loads are put forward. The discussion begins by reviewing the amount of offset increase due to a squall duration of 10.0 minutes in each direction of loading. Then the comparison will be reviewed concerning the maximum offsets due to environmental loads when induced by squalls with 2.5 and 5.0-minute durations of escalation. The offset analysis evaluates the movement in the x-axis and y-axis or surge and sway directions, respectively.

The highest percentage of the increase in the maximum offset values overall mooring lines for each loading direction in sea environment affected by a 10-minute squall in comparison to those without squall are contained in Table 12. The figures are distinguished for the case of extreme operational and survival conditions.

Table 12. the Highest Percentage of Increase in Maximum Offset due to 10-Minute Squall

Direction	**Operational Condition (1-year)**		**Survival Condition (100-year)**	
	Highest ∆ Offset		**Highest ∆ Offset**	
	***x* (%)**	***y* (%)**	***x* (%)**	***y* (%)**
0°	138	0	230	5
45°	***352***	56	***367***	60
90°	12	***65***	46	***115***
135°	261	60	159	73
180°	192	0	139	5

For an operational condition or 1-year environmental recurrence, the highest percentage of offset increase from the load without squall effect to the load induced by 10-minute squall, in the case of surge motion or x-axis, is attributable to the 45° load propagation reaching as much as 352%. The lowest percentage of offset increase in surge mode is related to 90° load propagation, which is in the order of 12%. While the highest rate of offset increase in sway mode or *y*-axis is caused by the 90° load direction, i.e., some 65%. There is no offsetting increase in the case of 0° and 180° load directions.

For survival conditions with a 100-year environmental recurrence, the highest percentage of offset increase in surge mode is also attributable to the 45° load propagation reaching the extent of 367%. The lowest rate of offset increase in surge mode is related to 90° load propagation, which is in the order of 46%. In the case of sway offset, the highest growth of 115% is experienced due to 90° load direction. Whereas the lowest offset increase brought about 0° and 180° load directions, which are not higher than 5%.

As shown in Table 13, to comprehend the offset fluctuations due to changes in squall duration of escalation, the maximum offset results from squall duration of 10 minutes per each direction of loading were compared with the offset results of environmental loading with squall escalation of 2.5 and 5.0 minutes. The values in the table show the offset intensities in meters. Tables 13 and 14 present the largest among maximum offsets, respectively, in the *x*-axis and *y*-axis directions, specifically for the operational condition of 1-year environmental loads. Whereas Tables 15 and 16 are for extreme survival condition under the influence of a 100-year environmental loads.

Table 13. the Largest of Maximum Offsets in *x*-axis Related to Variations in Squall Duration and Direction of 1-year Operational Load

	Offset in x-direction (m)				
	0°	**45°**	**90°**	**135°**	**180°**
Non-Squall	1.06	0.63	0.36	1.00	1.30
Squall 2.5 mins	***3.79***	***2.84***	***0.85***	***3.59***	***3.94***
Squall 5.0 mins	2.53	1.91	0.48	2.52	3.41
Squall 10.0 mins	3.14	2.34	0.53	3.00	3.74

Table 14. the Largest of Maximum Offsets in *y*-axis Related to Variations in Squall Duration and Direction of 1-year Operational Load

	Offset in y-direction (m)				
	0°	**45°**	**90°**	**135°**	**180°**
Non-Squall	***0.01***	5.71	5.75	5.78	0.04
Squall 2.5 mins	***0.01***	***12.97***	***12.99***	***13.31***	***0.08***
Squall 5.0 mins	***0.01***	11.21	11.13	11.58	***0.08***
Squall 10.0 mins	***0.01***	8.93	9.48	9.27	0.06

Table 15. the Largest of Maximum Offsets in *x*-axis Related to Variations in Squall Duration and Direction of 100-year Operational Load

	Offset in x-direction (m)				
	0°	**45°**	**90°**	**135°**	**180°**
Non-Squall	2.19	1.56	0.46	2.43	3.06
Squall 2.5 mins	6.65	***5.44***	0.96	***6.78***	***10.21***
Squall 5.0 mins	5.85	4.82	0.89	6.09	7.35
Squall 10.0 mins	***8.11***	5.41	***1.52***	5.41	7.32

Table 16. the Largest of Maximum Offsets in *y*-axis Related to Variations in Squall Duration and Direction of 100-year Operational Load

	Offset in y-direction (m)				
	0°	**45°**	**90°**	**135°**	**180°**
Non-Squall	0.01	7.91	7.01	9.06	0.06
Squall 2.5 mins	***0.02***	***15.48***	***13.92***	***15.37***	***0.13***
Squall 5.0 mins	***0.02***	14.07	12.60	14.77	0.12
Squall 10.0 mins	***0.02***	9.17	15.08	9.17	0.11

Examining Table 13, the largest of the maximum offset intensities in the direction of *x*-axis occurs when the environmental load propagates at 180° under the influence of squall with a 2.5-minute duration of escalation, reaching 3.94 m. While the largest of the maximum offset in the direction of *y*-axis, as shown in Table 14, is due to the load advancing at 135° with a 2.5-minute squall duration. The intensity of the offset in this direction reaches 13.31 m.

According to OCIMF [22], for the sake of the safety of FSO operation, the maximum offset value should not exceed 15% of water depth. In the case of the Belida oil field in the South Natuna Sea where the average depth is around 77.0 m, the maximum offset is limited to only 11.55 m. Referring to these rules and observing the results in Table 14, then the criteria will be violated by the *y*-axis offset if the 1-year recurrence environmental load propagates at 45°, 90° and 135° experience a magnification by a 2.5-minute squall. Here the *y*-axis offsets exceed the respective criteria by 1.42 m or 12.3%, 1.44 m or 12.5%, and 1.76 m or 15.2%. In fact, for the case of the operational environment load that propagates 135° combined with a 5.0-minute squall the criteria is also exceeded, but it is tiny, which is only 0.03 m or 0.25%.

The offset intensities, in conjunction with the extreme 100-year survival conditions, as shown in Table 15 and Table 16 may be described as follows. The largest of the maximum offsets in the direction of *x*-axis reaches 10.21 m due to environmental load propagation of 180° and induced by a 2.5-minute squall. In the case of the *y*-axis offsets, the highest of the maximum intensities extent to 15.48 m due to an environmental load advancing at 45° and affected by a 2.5-minute squall.

Although the largest of the maximum offsets in the direction *y*-axis is 15.48 m as stated above, in Table 16 there are still some other results that also exceed the criteria. The first group, if the extreme load of survival condition in the direction of 45°, 90° and 135° experienced a magnification by a 2.5-minute squall, then the *y*-axis offset will exceed the criteria, respectively, by 3.93 m or 34.0%, 2.37 m or 20.5%, and 3.82 m or 33.1%. The second group, if extreme loads in the same direction as before combined with a 5.0-minute squall, the *y*-axis offset exceeds the criteria by 2.52 m or 21.8%, 1.05 m or 9.1%, and 3.22 m or 27.9%, respectively. In the third group, if the extreme load with 90° direction interacts with a 10.0-minute squall, then the offset in *y*-axis will exceed the criteria by 3.53 m or 30.6%.

From the safety point of view, the y-axis offsets that exceed the criteria may not result in mooring line failures because it could be assured that the mooring line MBL is still far above the highest tension load that may occur. However, it is concerned that there is a possibility the excessive offset in the y-axis direction will cause damage to the riser and the FSO heeling, thus jeopardizing its stability. Further study of these aspects is considered essential to be pursued.

4. Conclusion

From the results of this study, there are a number of conclusions can be drawn. Squall with the duration of escalation in the span of 2.5, 5.0 and 10.0 minutes may instigate the increasing of significant wave height Hs by as much as, respectively, 60%, 50%, and 34%, for both 1-year recurrence operational and 100-year recurrence survival environmental conditions. This fact indicates that a shorter duration of escalation will magnify the wave elevation more extended time, during an overall 30 minutes of simulation time, hence generates a larger intensity of Hs. However, squall affects trivially on the change in wave peak period Tp, in general, the increase will not be higher than 1.2%.

The largest of maximum tensions that occur due to the five variations of environmental load propagation is found to be in the 45° direction when experiencing the squall magnification with a 2.5-minute duration of escalation. The intensity in operational and survival conditions reached 2,027 kN and 3,318 kN, respectively, on the mooring line L8. The intensity of these two largest tensions is still far below the MBL, which is 7,685 kN. The increase in the offset due to squall under operational conditions may reach 352% and 65%, respectively, for the x-axis and y-axis directions. Whereas under survival conditions, the increase can be as much as 367% and 115%. The largest of maximum offsets in x-axis for the operational condition is 3.94 m caused by the load propagating 180° when combined with a 2.5-minute squall. In contrast, the largest of maximum y-axis offsets reaches 13.31 m brought about the 135° load propagation if magnified by a 2.5-minute squall also. This y-offset intensity is some 15.2% higher than the limiting criteria of 11.55 m or 15% of the water depth, which is 77.0 m.

Under extreme survival conditions, the largest of maximum *x*-axis offsets is 10.21 m, due to 180° load propagation and a 2.5-minute squall. The largest of *y*-axis offset of up to 15.48 m arises due to the excitation of 45° environmental load and a 2.5-minute squall. This intensity is 34.0% greater than the criteria. Offset that exceeds the requirements is concerned as it may cause failures to the riser and endangering FSO stability. Further study of this aspect is considered essential to do. In general, this study shows that a squall with a shorter duration of escalation or gives a faster magnification in environmental load will lead to a more significant increase in the intensity of mooring tension and vessel offset.

Acknowledgements

Firstly, the authors would like to express their deepest gratitude to the senior officers of Medco E&P Natuna Ltd. who have given the permission to study the Belida FSO and at the same time provide all the necessary supporting data. Secondly, the authors are very grateful to the senior officers of PT Zee Indonesia for supporting this study by providing the software facilities for modeling.

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