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Analysis of Water Depth Variation Impact on CALM Buoy Performance for Shallow Water Condition

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Abstract: The SPM CALM Buoy is an offshore facility for loading/unloading crude oil. The SPM CALM Buoy in Indonesia is mostly operated in shallow water, so an analysis of the depth variation impact on the performance of the CALM Buoy is of necessity. The results of the analysis of the ship motion in free floating condition under the conditions of regular waves and spectral response show that the surge, sway, and yaw motions are influenced by depth variations, while the heave, roll, and pitch are influenced by frequency. For the CALM Buoy, all movements are affected by the depth variations. The results of the analysis in mooring condition show that the tension on the mooring line and offset on the CALM Buoy are affected by variations in depth and not affected by the towing force of the ship. The deeper the water area, the higher the values of the tension and offset. At a depth of 21 m to 42 m, a pre-tension of 10% of MBL is used, while at a depth of 50 m, a pre-tension of 15% of MBL is used since the initial pre-tension of 10% is unable to accommodate the movement of the CALM Buoy. This is because the second order wave load has a greater influence on moored structures such as the CALM Buoy.

Keywords: *CALM Buoy; offset; shallow water; second order; tension.*

Mathematics Subject Classification (2010): 76E07, 76E09.

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1 Introduction

Petroleum remains the main choice for addressing the needs for energy sources, that is, fuel for motor vehicles, industry, and power plants. Indonesia's production capacity of only around 800,000 barrels per day cannot meet the need for oil consumption reaching more than 2 million barrels per day [1]. This is because Indonesia only relies on its production from the old wells on land, that are of the colonial era. Based on the data from the Ministry of Energy and Mineral Resources, Indonesia still has oil reserves of 320 billion barrels situated off the west coast of Aceh. With the discovery of offshore oil reserves, offshore exploitation technology is needed to reap the advantage out of the potential of such discovery.

Since the petroleum exploitation is done offshore, it is necessary that a floating structure be built so as to be able to exploit and distribute petroleum. There are two ways to distribute the petroleum, that is, by flowing it through subsea pipelines and by using tankers. Distribution through subsea pipelines is considered not economical enough due to its high costs if the pipes should be installed in deep waters. So, distribution by using tankers is preferred because it is more economical.

The process of transporting crude oil from the drilling site to tankers is called offloading. Tankers require stability criteria during the offloading period, so a mooring system is required to maintain the motion limit of the ship against wave excitation. There are many configurations of mooring systems, among others, spread mooring, turret mooring, and single point mooring. The single point mooring type is a mooring system that can follow environmental conditions so that tankers can move following the waves without having to stop the offloading process.

One of the single point mooring types is SBM (Single Buoy Mooring) [2]. Single buoy mooring is a type of single point mooring using a buoy useful for mooring and connecting the riser to the tanker. Single Buoy Mooring mostly operates in shallow water because its function is to distribute oil from ships to storage depots. The buoys used for mooring systems greatly affect the strength and stability of the mooring system. The size of the buoy used must be in accordance with the size of the ship used during the offloading period because the incorrect motion response from the ship is a significant factor in influencing the stability of the buoy. The problems raised in this study include: what is the behavior of the CALM Buoy and tanker in free floating condition?, how does the difference in depth affect the tension on the mooring line and the offset on the Buoy? and what is the trend of the influence of depth variation on the level of the tension on the mooring line? The purpose of this study is to answer these three problems, the results are considered to be useful later as reference information for the interested companies.

2 Experiment

2.1 Instruments and materials

All segments of the Mooring Line are made of chains. For a long time, the chain has been the main choice in offshore operations because the chain has more strength than seabed aberration and makes a very significant contribution to anchor grip. All segments of the Mooring Line are made of a wire rope. Basically, this wire rope is lighter than the chain, therefore the wire rope has a higher restoring force in deep sea waters and requires lower pre-tension than the chain. To avoid lifting the anchor on the wire rope, a longer wire rope is needed than when using a chain. The wire rope is more susceptible to corrosion attack, therefore it requires extra care because mechanical damage due to corrosion is a more common factor causing failure. The Mooring Line is a combination of more than one chain segment and the wire rope. By combining the Mooring Line into more than one segment, namely the chain and wire rope, one will obtain the following advantages: a low pre-tension, high restoring force, larger holding anchor and resistance to aberration. These advantages make the Mooring Line with combined segments very suitable for application in the deep sea.

2.2 Work procedures

2.2.1 Theory

Various literatures and related theoretical basis are employed to support this research, starting from the effect of depth on the response of SPAR motion in deep water [3]. Based on the research, there is no significant change in depth variation when the object operates in deep water. However, when it is in shallow water, the change in depth variation has a significant effect on the response of the structure due to the energy difference (surge wave force) resulted from the difference in depth [4], [5], [6]. The difference in the response value of the structure movement in the free floating condition was analyzed by the frequency domain analysis method using the equation

$$M_{(\omega)}r + C_{(\omega)}r + K_{(\omega)}r = Xe^{i\omega t}, \tag{1}$$

where
$M_{(\omega)}$: mass matrix of frequency function (tons),
$C_{(\omega)}$: damping matrix of frequency function (ton/s),
$K_{(\omega)}$: stiffness matrix of frequency function (kN/m),
X : complex load vector giving information on load amplitude and phase at all degrees of freedom. The pattern $e^{i\omega t}$ sets the variation harmonics of the sample load with frequency.
r : displacement vector (m).

After the response value of the frequency-based structure movement is obtained, the response value of the structure in mooring state is found by the time domain analysis method using the equation

$$[m + A(\omega)]\ddot{x} + C(\omega)\dot{x} + D_1\dot{x} + D_2 f(\dot{x}) + Kx = q_{W1} + q_{WA}^1 + q_{WA}^2 + q_{CU} + q_{xet}, \tag{2}$$

where q_{W1} is the wind drag force, q_{WA}^1 is the wave drift of first order, q_{WA}^2 is the wave drift force of second order, q_{CU} is the current force, q_{xet} is the other external force.

When a time-based analysis (time domain analysis) is made, several outputs are obtained in the form of tension from the mooring line and hawser. In addition, the offset, heave, and roll/pitch of CALM Buoy are obtained [7], [8], [9], [10]. To find out the value of the tension occuring due to the holding back of the response of the structure resulted from wave excitation, the equation below is used.

$$T_{max} = T_H + wh, \tag{3}$$

where T_{max} is the maximum tension of the mooring rope (tons), T_H is the horizontal pre-tension (tons), w is the chain weight in water (ton/m), h is the water depth (m).

The tension value is affected by the ratio of the length of the mooring line to the depth of the water. In this analysis, the magnitude of the pre-tension value for each depth is made the same, which is 10% of the MBL [11].

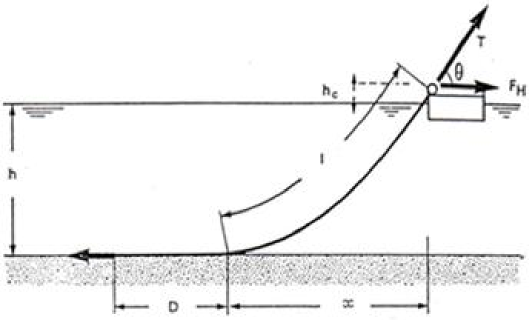

Figure 1: Setup of the Mooring Line.

The movement of the floating structure in the moored condition can be considered as a first order high frequency movement and a second order low frequency movement divided separately. The motion equation of the wave frequency [12] for the FPSO is

$$(M_{ij} + \mu_{ij})\ddot{x}_j^{(1)} + \int_0^\infty K_{ij}(\tau)\dot{x}_j^{(1)}(t-\tau)d\tau + C_{ij}x_j^{(1)} = F_i^{moor} + F_i^{wave(1)}, \tag{4}$$

where
$x_i^{(1)}$ is the wave frequency motion, $F^{wave(1)}$ is the first order wave force, F^{moor} is the mooring force, M is the inertia matrix FPSO.

The equation of low frequency motion of FPSO [12] is as below:

$$\begin{aligned}
(m+\mu_{11})\ddot{x}_1^{(2)} + \mu_{12}\ddot{x}_2^{(2)} + \mu_{16}\ddot{x}_2^{(2)} + (B_{11}+B_{wdd})\dot{x}_1^{(2)} &= F_1^{wind} + F_1^{current} + F_1^{wave(2)} + F_1^{moor} \\
\mu_{21}\ddot{x}_1^{(2)} + (m+\mu_{22})\ddot{x}_2^{(2)} + \mu_{26}\ddot{x}_6^{(2)} + B_{22}\dot{x}_2^{(2)} &= F_2^{wind} + F_2^{current} + F_2^{wave(2)} + F_2^{moor} \\
\mu_{61}\ddot{x}_1^{(2)} + \mu_{62}\ddot{x}_2^{(2)} + (I+\mu_{66})\ddot{x}_6^{(2)} + B_{66}\dot{x}_6^{(2)} &= F_6^{wind} + F_6^{current} + F_6^{wave(2)} + F_6^{moor}
\end{aligned} \tag{5}$$

where $x^{(2)}$ is the low frequency motion, B_{11}, B_{22}, B_{33} are the damping coeficients, B_{wdd} is the wave drift damping coeficient in the direction of the x-axis, $F_i^{current}$ is the current force, F_i^{wind} is the wind force, F_i^{moor} is the mooring force, $F_i^{wave(2)}$ is the second order wave drift force.

2.2.2 CALM Buoy

The CALM Buoy is a mooring system commonly used for loading/unloading processes as a connector between tankers and the fuel transit terminal. The #SPM150 CALM Buoy is one of the SPM owned by PT. Pertamina, operating off the coast of Tuban, having a configuration of 6 symmetrical mooring lines, a hull size of 11 m, an outer skirt diameter of 15 m, a water draft of 2.95 m, and an ability to accommodate vessels with a capacity of up to 150,000 DWT.

2.2.3 Environmental data

The environmental data used in this study are the data taken from the Tuban offshore environment, obtained from Sofec with a significant wave height of Hs = 3.1 m, a wave period of Tp = 6.9 sec, a wind speed of 11 knots, and a surface current speed of 0.75 m/sec. The depth variation is obtained from the calculation of environmental parameters, that is, the ratio of the wave number to the depth or non-dimensional water depth (kh) and based on structural parameters, that is, the ratio of depth to draft (D/T) [13].

Depth (m)	21	23	25	27	30	33	37	42	50
kh	1.3	1.4	1.5	1.6	1.8	2.0	2.2	2.5	3.0
D/T	1.2	1.3	1.4	1.5	1.7	1.9	2.1	2.4	2.9

Table 1: Calculation of Depth Variation.

The results of the calculation of depth variation for this study can be seen in Table 1. The selection of a low interval at the initial depth and a high interval at the final depth is due to the authors' desire to know a more specific downward trend when in shallow waters.

2.2.4 Structure modeling

The modeling of the ship structure and CALM Buoy in this study uses the software, while the analysis of the motion of the structure during mooring condition uses the Ariane software. For the modeling of the software, structural coordinate data are used to create a meshing to be used for hydrodynamic analysis. The meshing form of the ship structure and the CALM Buoy can be seen in the image below.

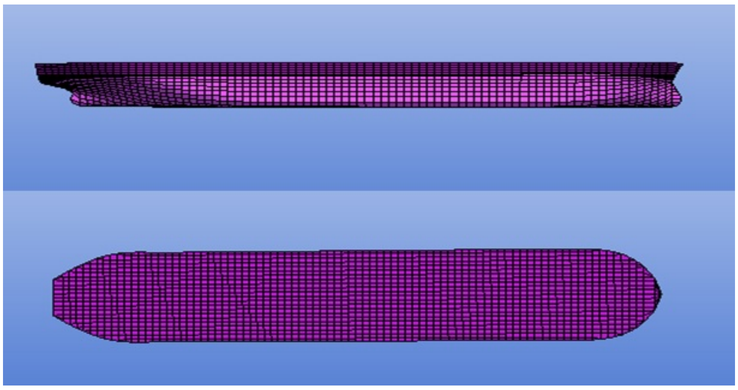

Figure 2: The results of modeling the structure of the ship on the software.

The analysis carried out on software is only to find out the characteristics of the object's motion in free-floating condition [14]. For further analysis, that is, the analysis of the mooring condition, mooring software is used. The analysis of mooring conditions is carried out under two conditions, that is, the inline mooring condition and between-line mooring conditions [15]. From Figure 4 below, the inline condition can be described as the ship is in a floating position parallel to the mooring line. This position indicates that there is only one mooring line that holds the ship when the ship is subjected to environmental loading in the form of waves or currents coming from the front of the

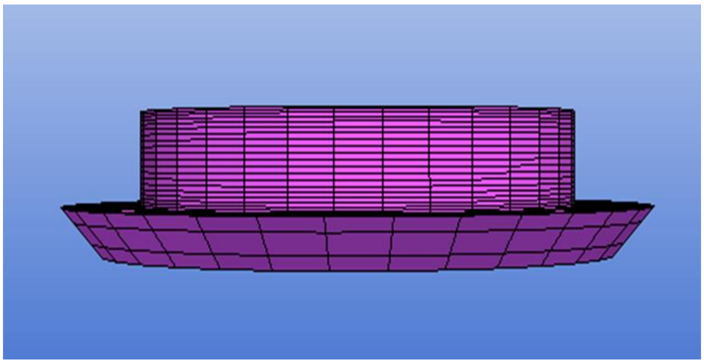

Figure 3: CALM Buoy modeling results on the software.

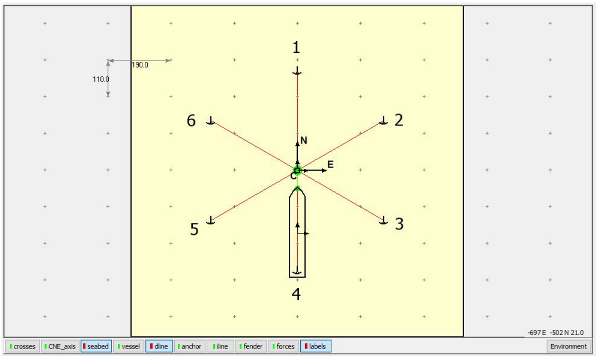

Figure 4: Inline conditions moored modeling on mooring software.

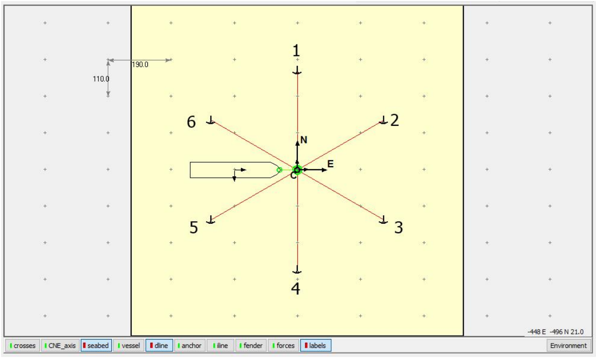

Figure 5: Inline conditions moored modeling on mooring software.

ship. From Figure 5, the between-line condition can be described as the ship is in a floating position between two mooring lines. This position indicates that there are two mooring lines that hold the ship when the ship is subjected to environmental loading in the form of waves or currents coming from the front of the ship. Therefore, the tension received by the mooring line in the between-line condition is smaller than in the inline condition because the load is distributed to two mooring lines.

2.2.5 Model validation

The validation criteria used refer to ABS (American Bureau of Shipping) of which the maximum value for displacement validation is 2% and, for other provisions, the maximum value is 1%.

3 Results and Discussion

After going through the data processing stage, the results and discussion are as follows. The discussion is to find out the effect of the depth variation on the performance of the CALM Buoy in offloading conditions. The performance of the CALM Buoy can be analyzed in terms of the magnitude of the tension on the mooring line, the offset, heave, and roll/pitch of the buoy. The CALM Buoy performance analysis is carried out with the help of mooring software using the time domain analysis method. The output data in the form of time history is then processed to obtain significant values to be used in the performance analysis.

3.1 Research location

The research site as shown in Figure 6 is in the Main Transit Terminal Facility, offshore of Tuban Regency, East Java Province, at the coordinates of 111°56′21″ east longitude and 06°42′48" south latitude. From Figure 6 below, it is known that the CALM Buoy and the ship are located off the coast of Tuban not too far from the mainland and not too deep.

Figure 6: The Research Location in Tuban.

3.2 Motion analysis of free floating conditions

The motion analysis of the ship and CALM Buoy in free-floating condition was made to determine the behavior or characteristics of structural motion on regular waves. The

RAO analysis was carried out at the depth referring to Table 1. For the ship's RAO, the highest values of the surge, sway, and yaw motions were affected by the depth of the water, while the highest values of the heave, roll, and pitch motions were affected by the magnitude of the frequency. For the RAO of the CALM Buoy, all the motions were affected by the depth variation condition.

3.3 Response analysis on random waves

The response analysis on random waves resulted in the same conclusion as that in the free-floating condition. This was because the results of the analysis on random waves follow those of the analysis in the free-floating condition.

3.4 Tension analysis on mooring line

The tension analysis on the mooring line was carried out in two conditions, using the time domain analysis method, that is, inline condition and between-line condition.

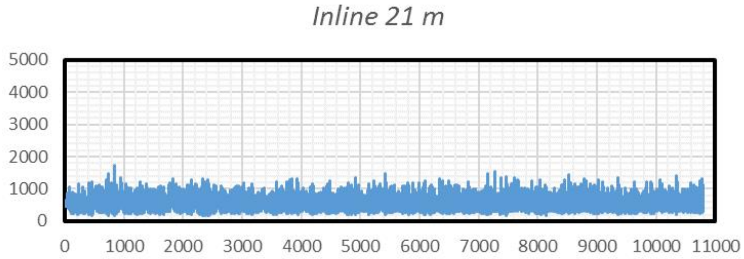

Figure 7: Example of value measurement of time history.

In the inline condition, the analysis was made only for the mooring line number 1. In the between-line condition, the analysis was made for the mooring lines number 2 and 3. This was due to the condition of the mooring line configuration in which, for both conditions, an analysis was made just for the mooring line having the greatest tension. The tension value for mooring line 1 can be seen in Table 2. For mooring lines 2 and 3, it can be seen in Table 3 and Table 4.

	Depth (m)								
Description	21	23	25	27	30	33	37	42	50
MEAN (KN))	541.19	552.05	450.72	553.27	567.14	568.91	586.61	617.26	664.37
Tension 1/3 highest (KN)	762.45	791.99	813.69	819.85	856.93	885.86	947.15	1043.80	1084.50
Tension 1/10 highest (KN)	912.88	960.47	995.54	1016.60	1089.20	1134.86	1232.90	1411.00	1500.00
Tension 1/100 highest (KN)	1175.60	1268.80	1320.00	1381.00	1520.00	1603.00	1788.20	2229.20	2483.00
MAX (KN)	1719.83	1841.95	1560.51	2033.80	2283.89	2536.75	2712.01	3612.01	4470.45
MIN (KN)	171.20	161.32	148.19	157.50	147.60	152.54	151.95	156.40	171.83

Table 2: Calculation of the Value of Tension on Mooring Line 1.

The tension values in inline and between-line conditions increased due to variation in depth. The significant value of tension for inline condition at a depth of 21 m to that of 50 m increased by 29%. The significant value of the tension for the between-line

	Depth (m)								
Description	21	23	25	27	30	33	37	42	50
MEAN (KN))	540.12	552.77	535.96	546.28	566.35	540.85	583.31	596.22	871.56
Tension 1/3 highest (KN)	708.58	719.22	742.62	764.88	780.27	801.65	868.36	905.53	1177.90
Tension 1/10 highest (KN)	853.13	854.21	886.41	922.96	1009.90	987.69	1084.80	1156.30	1421.70
Tension 1/100 highest (KN)	1080.50	1096.20	1150.00	1208.00	1385.50	1290.50	1468.00	1670.30	2071.00
MAX (KN)	1739.28	1832.96	1555.38	1804.56	2185.98	2134.09	2348.60	2679.82	4476.58
MIN (KN)	198.60	179.48	179.25	176.16	179.49	178.16	184.18	171.17	347.60

Table 3: Calculation of the Value of Tension on Mooring Line 2.

	Depth (m)								
Description	21	23	25	27	30	33	37	42	50
MEAN (KN))	539.33	546.34	531.79	542.31	558.72	540.78	579.78	598.78	875.14
Tension 1/3 highest (KN)	702.25	715.35	736.03	756.77	788.52	802.03	863.30	909.10	1189.10
Tension 1/10 highest (KN)	847.73	850.84	874.64	912.02	996.14	986.56	1078.80	1156.60	1449.20
Tension 1/100 highest (KN)	1057.80	1100.00	1120.00	1194.40	1356.40	1302.30	1494.80	1650.40	2162.00
MAX (KN)	1426.31	1824.89	1538.04	1727.19	2038.19	2524.84	2310.40	3026.76	4322.85
MIN (KN)	201.78	180.82	180.63	173.92	180.39	183.15	168.84	181.78	351.48

Table 4: Calculation of the Value of Tension on Mooring Line 3.

condition on the mooring line 2 and mooring line 3 at a depth of 21 m to that of 50 m increased by 39%. At a depth of 50 m, the tension value for the between-line condition was greater than that for the inline condition because the pre-tension value changed from 10% MBL to 15% MBL (minimum breaking load)

3.5 Calm Buoy offset analysis

The offset analysis for the mooring line was made under two conditions, that is, the inline condition and between-line condition. The offset for the inline condition can be seen in Table 5, and that for the between-line condition can be seen in Table 6.

	Depth (m)								
Description	21	23	25	27	30	33	37	42	50
MEAN (m))	0.37	0.44	0.55	0.56	0.69	0.80	1.01	1.30	1.49
Offset 1/3 highest (m)	0.71	0.85	0.99	1.08	1.32	1.53	1.92	2.43	2.84
Offset 1/10 highest (m)	0.92	1.11	1.27	1.40	1.71	1.96	2.44	3.08	3.67
Offset 1/100 highest (m)	1.21	1.47	1.66	1.88	2.28	2.60	3.19	4.00	4.83
MAX (m)	1.60	1.97	2.17	2.64	2.99	3.59	4.12	5.13	5.84

Table 5: Inline condition offset calculation.

The buoy offset in inline and between-line conditions increased due to depth variation. In the inline condition, at a depth of 21 m, the significant offset was 0.71 m, and it continued to increase to 2.84 m at a depth of 50 m. In the between-line condition, at a depth of 21 m, the value was 0.68 m and continued to increase up to 2.04 m at a depth

	Depth (m)								
Description	21	23	25	27	30	33	37	42	50
MEAN (m))	0.35	0.40	0.45	0.52	0.67	0.72	0.9	1.05	0.85
Offset 1/3 highest (m)	0.68	0.77	0.86	1.00	1.27	1.36	1.72	2.04	1.61
Offset 1/10 highest (m)	0.88	0.98	1.12	1.31	1.63	1.74	2.23	2.66	2.07
Offset 1/100 highest (m)	1.18	1.37	1.50	1.80	2.17	2.28	2.94	3.59	2.76
MAX (m)	1.55	1.99	1.97	2.54	2.8	3.53	3.89	4.47	3.70

Table 6: Between-line condition offset calculation.

of 42 m, then decreased at a depth of 50 m to 1.16 m. The significant decrease in the tension value was due to the difference in the pre-tension values, that is, from 10% MBL to 15% MBL.

3.6 Motion response analysis of Calm Buoy in moored condition

The analysis of the motion response of the CALM Buoy in moored condition covered heave and roll/pitch motions. These motions were the performance parameters of the CALM Buoy. The values of these motions can be seen in Table 7 and Table 8.

	Depth (m)								
Description	21	23	25	27	30	33	37	42	50
MEAN (m))	0.84	0.87	0.92	0.96	1.02	1.08	1.15	1.23	1.45
Heave 1/3 highest (m)	0.91	0.95	1.00	1.04	1.10	1.17	1.25	1.37	1.62
Heave 1/10 highest (m)	0.95	0.99	1.04	1.08	1.15	1.21	1.31	1.45	1.72
Heave 1/100 highest (m)	1.00	1.05	1.10	1.14	1.21	1.29	1.40	1.58	1.88
MAX (m)	1.13	1.12	1.19	1.23	1.34	1.48	1.92	1.77	2.10

Table 7: Calculation of the value of heave of the Calm Buoy.

The heave value had an upward trend based on depth variation. At a depth of 50 m it showed a decrease due to difference in pre-tension values.

3.7 Tension trend based on depth variation

For the inline condition, the trend of significant tension values was only analyzed for mooring line 1. Whereas for the between-line condition, the analysis was made for mooring lines 2 and 3 because the trend value was based on the mooring line with the greatest tension. The trend of significant changes in tension values based on the depth variation can be seen in Figure 8, Figure 9 and Figure 10.

	Depth (m)								
Description	21	23	25	27	30	33	37	42	50
MEAN (deg))	6.80	8.26	8.85	8.90	9.75	9.80	11.10	12.90	10.20
Roll/Pitch 1/3 highest (deg)	12.80	16.06	16.95	17.37	18.50	18.62	21.20	25.74	20.10
Roll/Pitch 1/10 highest (deg)	16.60	20.59	21.71	22.18	23.87	24.25	27.24	34.50	26.22
Roll/Pitch 1/100 highest (deg)	21.90	26.39	27.56	28.31	31.44	34.70	35.90	46.98	35.11
MAX (deg)	29.40	33.22	33.50	33.80	40.27	45.00	48.78	59.50	44.00

Table 8: Calculation of roll/pitch of the Calm Buoy.

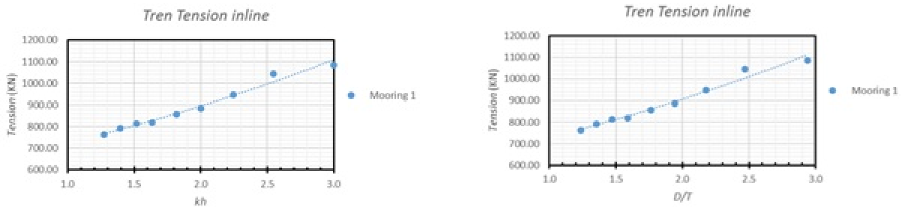

Figure 8: Tension on mooring line 1, the trendline in inline condition based on kh and D/T.

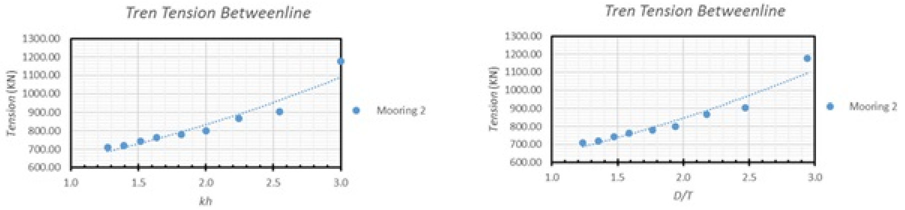

Figure 9: Tension on mooring line 2, the trendline in between-line condition based on kh and D/T.

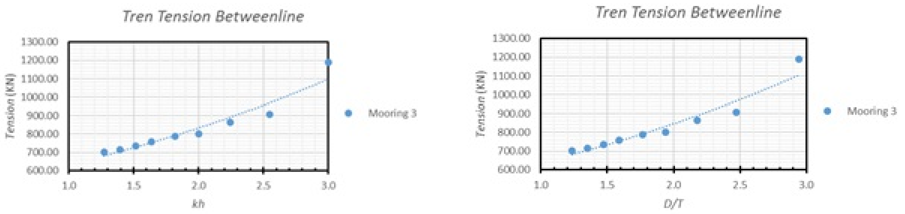

Figure 10: Tension on mooring line 3, the trendline in between-line condition based on kh and D/T.

The significant tension value in the inline condition based on both environmental and structural parameters has an upward trend based on depth variation. The tension trend in inline condition starts to look steady within a depth of 42 m up to that of 50 m. For the significant tension value in the between-line condition, it is not known at what depth the tension trend starts to stabilize because at a depth of 50 m, a pre-tension value different from that of the previous depth is used.

4 Conclusion

The maximum value of the ship's RAO motion varies in accordance with the depth of the water. The maximum values of the surge, sway, and yaw motions are affected by the difference in depth, while the heave, pitch, and roll are affected by the frequency. The maximum RAO value of all motions of the CALM Buoy is affected by the difference in depth.

The value of the ship's response in the random waves for the surge, sway, and heave motions is affected by the depth variation, while for roll, pitch and yaw motions, it is not affected by the depth variation. The response value follows that of the RAO value. The response value of the CALM Buoy in the random waves for all motions is affected by variation in depth because the response value follows that of the RAO value, whereas the CALM Buoy motion is not affected by changes in depth.

The tension on the mooring line for both inline and between-line conditions is affected by variation in depth. If in the analysis of the movement of the structure, the deeper the water area, the smaller the movement of the structure, then in the analysis of the tension on the mooring line, it has the opposite value. The tension in the inline condition from a depth of 21 m to 50 m increased by 29%, while for the between-line condition, it increased by 39%. This is because the resulting tension is caused by the increase in the heave and offset values at depth variation.

The offset of the CALM Buoy in both inline and between-line conditions is affected by variation in depth. The highest offset in inline condition occurs at a depth of 50 m up to 5.84 m. At the same time the farthest offset in the between-line condition occurs at a depth of 48 m up to 4.47 m, this is because in the between-line condition, at a depth of 50 m, a pre-tension of 15% MBL is used. The tension in the mooring line for both inline and between-line conditions has a trend of increasing values along with increasing depth. The significant tension value in the inline condition at a depth of 21 m is 762.45 KN and continues to increase until a depth of 50 m, at which the significant tension is 1084.5 KN. The significant tension value in between-line condition at a depth of 21 m is 708.58 KN, and it continues to rise, at a depth of 50 m, the significant tension reaches 1189.1 KN. For the inline condition, the tension value starts to stay steady at a depth of 42 m up to 50 m. For the between-line condition, it is not known at what depth the tension trend starts to be steady because at a depth of 50 m, a pre-tension is different from that at the previous depth so that the tension trend seems to increase significantly.

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