**International Journal of Offshore and Coastal Engineering**
Vol.8 | No. 2 | pp. 65 – 74 | November 2024
e-ISSN: 2580-0914
© 2024 Department of Ocean Engineering – ITS

Submitted: February 15, 2024 | Revised: April 1, 2024 | Accepted: May 6, 2024

# Analysis of the Global Structural Strength of a 35,000 DWT Single Point Mooring (SPM) Buoy Under Wave Loads

Elsa Rizkiya Kencana[a,], Muhammad Fatkhurrozi[a], Alvin Aziz Nugraha[a] and Olga Wulandari Kelen[b]

[a)] Ocean Engineering Department, Institut Teknologi Sumatera, South Lampung, Indonesia
[b)] Banner SPM Terminals Pty. Ltd., Australia
*Corresponding author: elsa.rizkiya@kl.itera.ac.id

## ABSTRACT

*Single Point Mooring (SPM) systems are offshore structures facilitating cargo transfer between tankers and refineries in deeper waters to accommodate larger vessels. The marine environment at SPM sites often features unstable and extreme wave conditions, making it essential to understand the SPM's response to these forces. SPMs include an anchor system with mooring lines secured to the seabed. Evaluating the stress on these lines and the buoy structure under environmental loads is crucial. This research models the SPM structure using dimensional data and mooring line specifications. The hypothesis posits that, based on the significant wave height and 100-year wave period in the Balongan Sea, as well as the minimum breaking load value for a 35,000 DWT SPM, the maximum tension in the mooring lines is 956 kN, which is below 2261 kN. It means safe based on API RP 2KS (2005) standards. Thus, the mooring lines are safe during operations under 100-year environmental loads with a maximum tension of 1732 kN. The maximum stress on the SPM buoy structure is 1.87 MPa and 3.38 MPa in ULS and ALS conditions, respectively.*

**Keywords:** *Single Point Mooring, Response, Stress*

## 1. INTRODUCTION

Indonesia is a country rich in natural resources, including oil and gas. PT Pertamina RU VI Balongan distributes oil and gas products across regions and provinces using tankers. These tankers need auxiliary or supporting facilities for mooring, such as single-point moorings (SPM). The Single Point Mooring (SPM) is a floating buoy structure positioned in the water that serves as a mooring facility for tankers and acts as a connection between tankers and refineries during the loading or unloading of cargo. The SPM is located in deeper waters than jetty mooring facilities to accommodate larger tankers that cannot dock at jetties. The SPM is subject to unstable and extreme wave conditions, given its offshore location. Therefore, it is crucial to analyse the motion response of the SPM to wave loads. SPM has an anchor system component, an anchorage system for the buoy body structure consisting of mooring lines anchored to the seabed. It is also important to know the tension value on each mooring line due to wave loads and the stress on the SPM buoy structure due to wave loads and tension from mooring lines. This research analyses the motion response, mooring line tension, and structural stress of a single-point mooring (SPM) under wave loads. The study focuses on six degrees of freedom motion, excluding tankers, with 100-year return period wave loads from various directions. Current wind loads and anchor grip strength are not considered. The hypothesis suggests that the maximum mooring line tension and structural stress are within safe limits according to [1] and [2] standards, ensuring the SPM's stability and safety under extreme wave conditions.

## 2. SINGLE POINT MOORING

Single Point Mooring (SPM) has emerged as an alternative to seabed pipelines for oil transportation from offshore producing facilities [3]. Initially designed for smaller boats in protected, shallow waters, SPM systems can handle up to 150,000 DWT tankers, enabling frequent and safe docking and loading procedures. Over time, these systems have evolved to withstand severe offshore conditions and deeper water. In SPM operations, the loading terminal, the buoy, is the sole point of reference for mooring. Various hoses typically assist oil transfer in addition to a single elastic mooring line, or hawser, that connects the terminal to the ship's bow [4].

There are three typical mooring systems for buoys: chain-catenary mooring, semi-taut mooring, and inverse-catenary mooring. To determine the mooring system depends on factors like water depth, cost, and deployment strategy. Chain-catenary mooring is often used in shallow waters due to its simple design.

Licensed under a Creative Commons Attribution 4.0 International License (URL: http://creativecommons.org/licenses/by/4.0/)

A mooring chain is used for water depths under 50 meters, but a cable is added to the upper section for deeper waters to reduce weight. Although affordable, this method is limited to shallow waters, struggles against strong winds and waves, and can harm the seabed as the chain drags along the ocean floor [5].

## 3. RESPONSE AMPLITUDE OPERATOR

The Response Amplitude Operator (RAO), or transfer function, represents how a structure responds to wave elevations across various frequencies. It converts wave forces into the dynamic motion characteristics of a structure. The RAO diagram typically has frequency on the x-axis and amplitude on the y-axis, showing movement in different modes. For translational motions (surge, heave, sway), RAO is the ratio of the structure's amplitude to the incident wave amplitude, both in meters. For rotational motions (roll, yaw, pitch) [6], RAO is the ratio of the rotational amplitude (in radians) to the wave slope, calculated using the wave number. The RAO equations [7] are given as follows:

$$\text{RAO}(\omega) = \frac{Z(\omega)}{\zeta_0(\omega)} \text{ (m/m)} \qquad (1)$$

$$\text{RAO}(\omega) = \frac{\zeta_{k0}}{k_0\zeta_0} = \frac{\zeta_{k0}}{(\omega^2/g)\zeta_0} \text{ (rad/rad)} \qquad (2)$$

Where,
$Z(\omega)$ = structure amplitude (m)
$\zeta_0(\omega)$ = wave amplitude (m)
$\theta(\omega)$ = rotational amplitude (degree/rad)
k = wave number

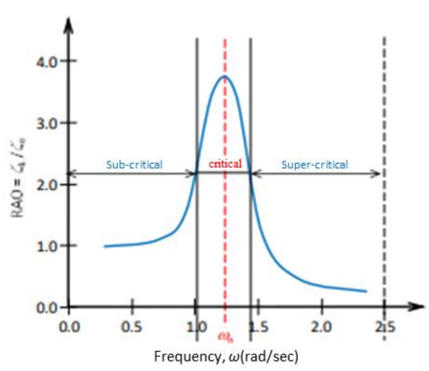



Figure 1. The general shape of the floating building motion response graph [7]

The rotational motion response amplitude value results can be converted into units of degrees (°) by changing the value of 1 rad to 57.3°.The motion response curve of floating structures is divided into three parts (see Figure 1):

a. Sub-critical region: At low frequencies (long waves), the structure moves with the wave, with an amplitude nearly equal to the wave's amplitude, known as contouring.
b. Critical region: The curve peaks at the natural frequency,
c. causing resonance, where the structure's motion exceeds the wave amplitude.
d. Super-critical region: At high frequencies (short waves), the motion response decreases, making the structure appear to move on relatively flat water, termed platforming.

## 4. MOORING TENSIONS

Movement of ships or floating objects and environmental factors cause tension in the mooring line. This tension can be classified into two types: mean tension and maximum tension. Mean tension is the tension in the mooring line related to the average displacement of the vessel. Meanwhile, maximum tension is mean tension influenced by wave frequency and low-frequency tension. Based on [1], the maximum tension can be determined by the following equation:

$$T_{max} = T_{mean} + T_{lf_{max}} + T_{wf_{sig}} \qquad (3)$$

$$T_{max} = T_{mean} + T_{wf_{max}} + T_{lf_{sig}} \qquad (4)$$

Where,
$T_{mean}$ = mean tension (N)
$T_{max}$ = maximum tension (N)
$T_{wf_{max}}$ = maximum wave frequency tension (N). The stress experienced by the mooring lines *of* the structure due to the structure's response at the maximum wave frequency.
$T_{wf_{sig}}$ = significant wave frequency tension (N). The stress experienced by the mooring lines *of* the structure due to the structure's response to the significant wave frequency.
$T_{lf_{max}}$ = maximum low-frequency tension (N). The stress experienced by the mooring lines *of* the structure due to the structure's response at the maximum low frequency.
$T_{lf_{sig}}$ = significant low-frequency tension (N). The stress experienced by the mooring lines *of* the structure due to the response of the structure at a significantly low frequency.

The strength analysis of the mooring system is carried out by considering the following limitations:

1. Ultimate Limit State (ULS) is an analysis to prove that each mooring line has the strength to accept loading from environmental loads under extreme conditions.

2. Accidental Limit State (ALS) is an analysis to ensure that the remaining mooring lines still have the strength to withstand the loads that occur if one of the *mooring lines* fails or breaks.

To ensure a mooring system design meets safety requirements, the tension in each mooring line should be checked to confirm it stays within permissible limits that satisfy safety factor criteria. The limit of the tension value on the mooring line and safety factor based on [1] is shown in the following table:

Table 1. Tension limit criteria and safety factor mooring line.

| Condition | Percent of MBS | Safety Factor |
|---|---|---|
| Intact (ULS) | 60 | >1.67 |
| Damage (ALS) | 80 | >1.25 |

The safety factor equation is:

$$\text{Safety Factor} = \frac{\text{Minimum Breaking Load}}{\text{Maximum Tension}} \quad (5)$$

### 4.1 Tension

Normal stress is the concentration of force at a point perpendicular or normal to the unit area. The normal stress equation is written as follows [8]:

$$\sigma = \lim_{\Delta A \to 0} \frac{\Delta F}{\Delta A} \quad (6)$$

Where,
σ = normal stress(N/m$^2$)
F = force acting in the direction perpendicular or normal to the cross-section (N)
A = cross-sectional area (m$^2$)

Shear stress is the concentration of force at a point parallel to the cross-section. The equation is written as follows [8]:

$$\tau = \lim_{\Delta A \to 0} \frac{\Delta V}{\Delta A} \quad (7)$$

Where,
τ = shear stress (N/m$^2$)
V = force acting in the direction parallel to the cross-section (N)

Von Mises stresses occur in three-dimensional elements with stresses acting in the direction of the x, y, and z axes. The principal stresses (σ1, σ2, σ3) can be determined based on each axis by calculation of the stress components with the following equations:

$$\begin{bmatrix} \sigma_x - \sigma_0 & \sigma_{xy} & \sigma_{xz} \\ \sigma_{xy} & \sigma_y - \sigma_0 & \sigma_{yz} \\ \sigma_{xz} & \sigma_{yz} & \sigma_z - \sigma_0 \end{bmatrix} = Q \quad (8)$$

Where,
$\sigma 0$ = stress acting on the main axis
$\sigma x$ = stress in the x-axis direction
$\sigma y$ = stress in the y-axis direction
$\sigma z$ = stress in the z-axis direction
$\sigma x$y = xy-axis directional stress
$\sigma x$z = xz-axis directional stress
$\sigma y$z = yz-axis directional stress

Combining all the main stresses in an element is a method to find the maximum stress value at that point. One way to calculate the combined stress is by using the Von Mises equation. The Von Mises equation is written as follows:

$$\sigma_{vm} = \frac{1}{2}\sqrt{(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_x - \sigma_z)^2 + 6(\tau_{xy}^2 + \tau_{yz}^2 + \tau_{xz}^2)} \ldots.. \quad (9)$$

With:
$\sigma_{vm}$ = Von Mises stress
$\sigma x$ = stress in the x-axis direction
$\sigma y$ = stress in the y-axis direction
$\sigma z$ = stress in the z-axis direction
$\tau x$y = shear stress in the xy-axis direction
$\tau$xz = shear stress in xz-axis direction
$\tau$yz = shear stress in the yz-axis direction

**4.2. Pressure**

Pressure is the force acting on a unit area, so it is defined in the following equation:

$$P = \frac{F}{A} \quad (10)$$

Where,
P = pressure (N/ m$^2$)
F = perpendicular force applied (N)
A = cross-sectional area (m$^2$)

Hydrostatic pressure is the pressure caused by a liquid on a unit area with a certain depth, which is defined by the following equation:

$$P_h = \rho \times g \times h \quad (11)$$

Where,
$P_h$ = Hydrostatic Pressure (Pa)
ρ = density of liquid (Kg/m$^3$)
g = gravitational acceleration (m/s$^2$)
h = depth (m)

## 5. METHODOLOGY

This research was conducted at PT Pertamina RU VI Balongan, Indramayu. The location map of the 35,000 DWT SPM research object with the coordinate position 06°16'24.78" LS / 108°28'00.65" BT is shown in Figure 2.

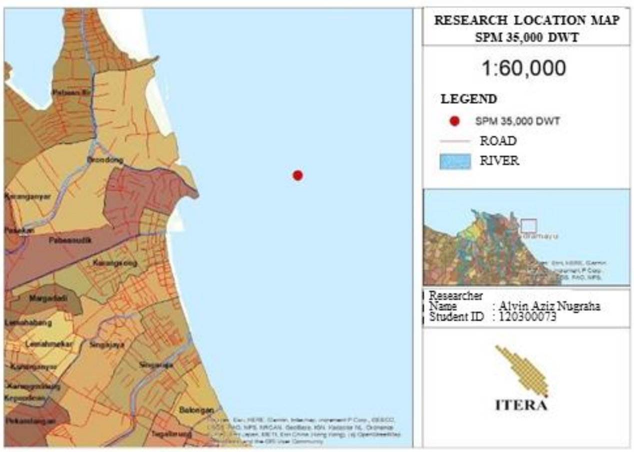



Figure 2. Research location map.

In this study, the analysis of motion response, tension mooring lines, and stress on the SPM structure was carried out using *software* assistance. The flow of work in this study can be seen in the flow chart in Figure 3. Data of this research are presented in Tables 2, 3, and 4. After collecting data, Structure Modeling was done using modeling structure software, focusing on the buoy body and skirt. Then, the model validation was compared by hydrostatic data from software with existing SPM data, ensuring model accuracy within a 2% tolerance limit. Hydrodynamic and mooring analysis software was utilised for motion response analysis to obtain RAO and response spectra using frequency domain simulation methods. Mooring line tension analysis identifies maximum tension using the same software as motion response analysis, with a safety factor calculated based on time domain simulation and code standards for ULS and ALS conditions. Using the finite element method software, a global stress analysis was employed to assess von Mises's stress, ensuring it stayed below 90% of the material's yield strength. The conclusion covers structure movement, mooring line tension, and maximum global stress.

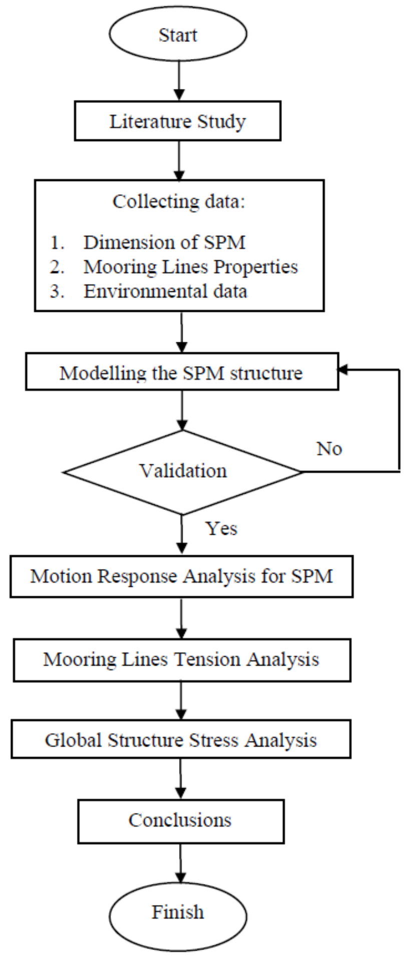



Figure 3. Flowchart of research.

Table 2. Dimension data of SPM 35,000 DWT. [9]

| Data | Value | Unit |
|---|---|---|
| Material | Steel | |
| Outer Diameter | 10.03 | m |
| Inner Diameter | 3.57 | m |
| Skirt Outer Diameter | 15.47 | m |
| Skirt Baseline | 0.50 | m |
| Draft | 2.00 | m |
| Displacement | 253.91 | Ton |

Source: PT. Pertamina RU VI Balongan

Table 3. Mooring Lines Properties [9]

| Data | Value | Unit |
|---|---|---|
| Type | Chain | |
| Number of Legs | 6 | |
| Anchoring Pattern | 60 | ° |
| Grade | R3 | |
| Diameter | 64 | mm |
| Minimum Breaking Load (MBL) | 3551 | kN |
| Depth (h) | 15.6 | m |
| Stiffness (AE) | 413696 | kN |

Table 4. Wave parameter data

| Data | Value | Unit |
|---|---|---|
| Significant Height (Hs) | 4.5 | m |
| Significant Period (Ts) | 6.8 | s |
| Peak Period (Tp) | 8.7 | s |

## 6. RESULT AND DISCUSSION

Modelling of the SPM structure in this study was carried out using software for the main structure, namely buoys, and skirts, and then modelling of mooring lines was carried out using hydrodynamic and mooring analysis software. Figure 4 shows the 35,000 DWT SPM modeling results using the software. SPM modelling was validated in this study by comparing hydrostatic data in the form of displacement issued by software with the data obtained. The validation criteria are based on code standards [6] with a maximum displacement value validation tolerance limit of 2%. The validation results obtained are as in Table 5. After the SPM model geometry is validated and meets the criteria, SPM modelling is carried out in hydrodynamic and mooring analysis software (Figure 5) using the SPM model geometry that has been created before. It requires input of point of mass and moment of inertia data. The results of these values obtained from the calculation are in Table 6.

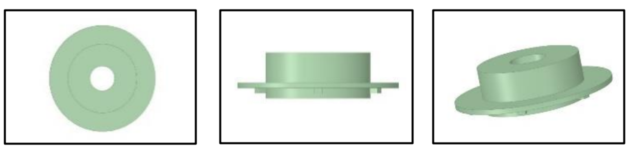


Figure 4. Geometry model of SPM structure modelling results. Top view (left), front view(center), and isometric view (right).

The software modeling process modeled the mooring lines connected to the SPM structure. Based on the obtained properties of the mooring lines, six mooring lines were modelled in this study with a symmetrical installation configuration and an anchoring pattern of 60°. The mooring lines used are catenary chains [10]. According to the calculations based on Faltinsen's research (1998) [11], all six mooring lines in this study were designed to have the same length.

Table 5. SPM modeling validation value results

| Data | Unit | Value | Model | Error | Status |
|---|---|---|---|---|---|
| Outer diameter | m | 10.03 | 10.03 | 0 % | Valid |
| Inner diameter | m | 3.57 | 3.57 | 0 % | Valid |
| Skirt diameter | m | 15.47 | 15.47 | 0 % | Valid |
| Buoy height | m | 4.4 | 4.4 | 0 % | Valid |
| Buoy draft | m | 2.8 | 2.8 | 0 % | Valid |
| Displacement | ton | 253.91 | 254.51 | 0.24 % | Valid |

Table 6. SPM modeling validation value results

| Data | Value | Unit |
|---|---|---|
| X | 0 | m |
| Y | 0 | m |
| Z | -1.65 | m |
| $I_{xx}$ | 2697238.42 | $kg.m^2$ |
| $I_{vy}$ | 1572572.86 | $kg.m^2$ |
| $I_{zz}$ | 1572572.86 | $kg.m^2$ |
| Displacement | 253.91 | ton |

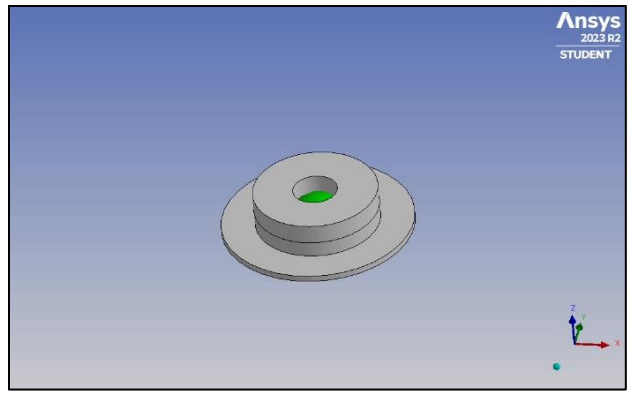



Figure 5. SPM model in hydrodynamic and mooring analysis software

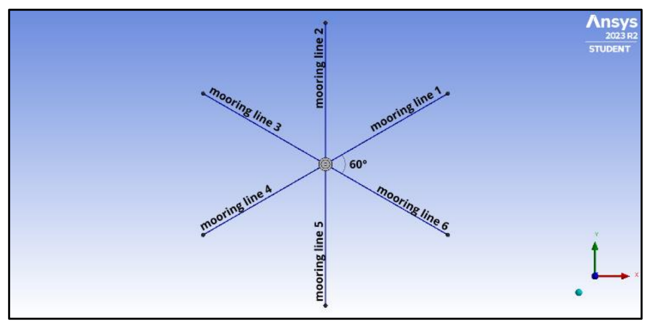



Figure 6. Mooring line schematic in software

### 6.1. Structure Motion Response Analysis

This section analyses the motion behavior characteristics of a 35,000 DWT SPM structure, resulting in RAO values for head seas (180°), quartering seas (225° and 315°), and beam seas (270°). RAOs are assessed across six degrees of freedom: surge, sway, heave, roll, pitch, and yaw under regular wave conditions.

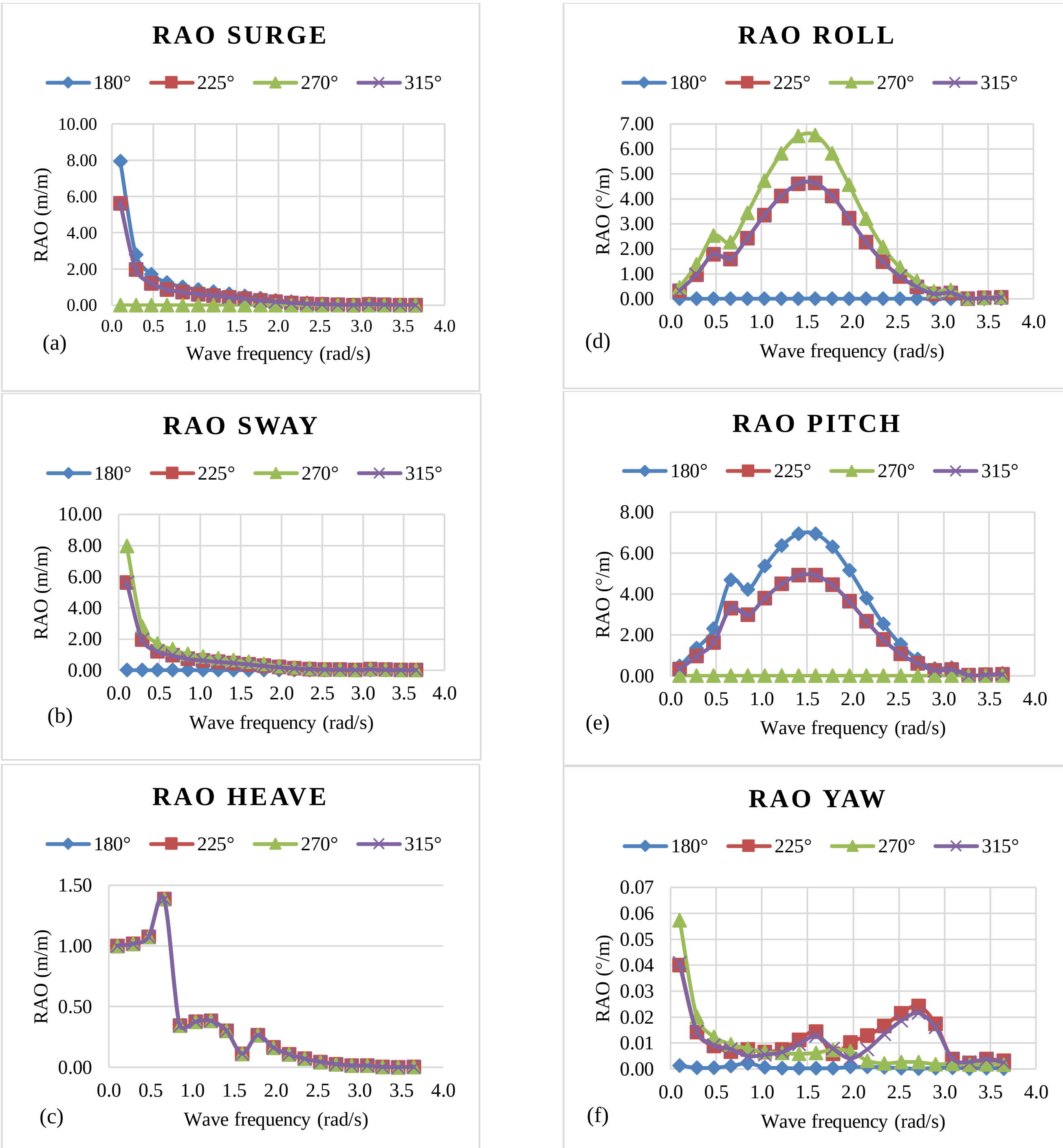



Figure 7. RAO chart of SPM in 6 motions: (a) surge, (b) sway, (c) heave, (d) roll, (e) pitch, and (f) yaw

The RAO graphs plot wave frequency (x-axis) against RAO values (y-axis). Surge RAO is largest at 180°, decreasing slightly at 225° and 315°, with minimal effect at 270°. Sway RAO peaks at 270°, with similar trends for 225°, 315°, and 180°. Heave RAO shows a sharp increase at 0.6 rad/s, indicating pitch coupling. Roll RAO peaks at 6.5 deg/m at 1.5 rad/s, mainly at 270°, with minimal impact at 180°. Pitch RAO, dominated by 180°, peaks at 6.9 deg/m, while yaw motion is most significant at 225° and 315° and nearly disappears at 180°. All results are shown in Table 7.

Table 7. Maximum RAO on SPM

| Mode | Loading direction | | | | Maxi mum |
|---|---|---|---|---|---|
| | $180^0$ | $225^0$ | $270^0$ | $315^0$ | |
| Surge (m) | 7.95 | 5.95 | 5.95 | 0 | 7.95 |
| Sway (m) | 0 | 5.95 | 7.95 | 5.95 | 7.95 |
| Heave (m) | 1.39 | 1.39 | 1.39 | 1.39 | 1.39 |
| Roll (deg) | 0 | 4.75 | 6.55 | 4.75 | 6.55 |
| Pitch (deg) | 6.94 | 4.35 | 0 | 4.35 | 6.94 |
| Yaw (deg) | 0.0005 | 0.04 | 0.06 | 0.04 | 0.06 |

In translational motion, the largest RAO values are found in surge and sway movements, with a value of 7.95m/m, meaning that per one meter of wave amplitude, there is a change in motion at SPM of 7.95 meters with surge and sway movements. In rotational motion, the largest RAO value is found in pitch motion with a value of 6.94°/m, meaning that per one meter of wave amplitude, there is a change in motion on the SPM of 6.94° with pitch motion.

### 6.2. Mooring lines tension analysis

In this section, the tension analysis on the mooring lines is carried out to determine the maximum tension value on each mooring line with parameter loading and predetermined wave direction [12]. The analysis is carried out using hydrodynamic response software with a time domain simulation method that produces tension values on each mooring line and is displayed in graphical form with the x-axis as time (s) and the y-axis as force (kN), the length of time the simulation is carried out based on [13] the provisions of 10800 seconds. Analysis is also carried out with loading conditions at Ultimate Limit State (ULS) and Accidental Limit State (ALS) conditions. The results of the maximum tension of the mooring lines will be compared with the maximum tension limit criteria based on [1]. The following are the results of the tension analysis on the mooring lines.

For analysis under ULS conditions, the safety factor for the chain is 1.67, the minimum breaking load of the chain is 3551 kN, and the maximum permissible tension value limit using equation 2.5 is 2126 kN. So, the maximum tension received by the mooring lines must not exceed 2126 kN. Table 8 summarises the maximum tension value on each mooring line. Based on the table of results of the maximum tension value on each mooring line, it is found that all mooring lines have a maximum tension value that meets the maximum permissible tension limit criteria of 2126 kN.

Table 8. Results of maximum tension value of mooring lines ULS condition

| Mooring Line | Maximum permissible tension (kN) | Maximum tension (kN) | Description |
|---|---|---|---|
| 1 | 2126 | 250 | allowable |
| 2 | 2126 | 304 | allowable |
| 3 | 2126 | 470 | allowable |
| 4 | 2126 | 826 | allowable |
| 5 | 2126 | 956 | allowable |
| 6 | 2126 | 822 | allowable |

For analysis under ALS conditions, the safety factor for the chain is 1.25, and the minimum breaking load of the chain is 3551 kN; then, with equation 2.5, the maximum permissible tension value limit is 2841 kN. Table 9 summarises the maximum tension value on each mooring line with each scenario of one failed mooring line. All the scenarios are in allowable condition, which means the SPM can endure the ALS condition.

Table 9. Summary of maximum tension value results in ALS condition

| Mooring Line Failure | Maximum Tension in Mooring Line (kN) | | | | | |
|---|---|---|---|---|---|---|
| | 1 | 2 | 3 | 4 | 5 | 6 |
| 1 | | 660 | 166 | 166 | 457 | 1503 |
| 2 | 526 | | 901 | 349 | 202 | 347 |
| 3 | 119 | 663 | | 1512 | 456 | 164 |
| 4 | 64 | 143 | 1001 | | 1732 | 375 |
| 5 | 116 | 87 | 185 | 1577 | | 1572 |
| 6 | 530 | 143 | 97 | 379 | 1728 | |

### 6.3. Maximum significant wave height limit

This section presents simulations of mooring line loading with varying significant wave heights (Hs) greater than the initial Hs value of 4.5 m while keeping the peak period fixed at 8.7 seconds. The simulations continue until the maximum tension in the mooring lines exceeds the allowable limit of 2126 kN under ULS conditions. The following summarises the simulation results for the maximum permissible Hs height.

Table 10. Maximum tension for maximum significant wave height limit

| Heading | Maximum tension (kN) | | | |
|---|---|---|---|---|
| Max Hs | $180^0$ | $225^0$ | $270^0$ | $315^0$ |
| 5 | 916 | 1462 | 1638 | 1455 |
| 5.5 | 1525 | 2287 | 2462 | 2250 |

The results indicate that at a 180-degree heading, for significant wave heights of 5 and 5.5 meters, all conditions remain within the safe category, as the maximum tension remains below 2126 kN. However, at a 225-degree heading, with a Hs of 5.5 meters, the maximum tension produced is 2287 kN on mooring line 4, rendering the condition unsafe. This also occurs at 270-degree and 315-degree headings, generating 2462 and 2280 kN on mooring lines 5 and 6, respectively. Therefore, the Hs height limit for safe SPM operation is 5 meters, as the maximum tension remains below 2126 kN in all headings.

**6.4. Global strength analysis of SPM structure**

The analysis aimed to determine the maximum stress values on the SPM structure by applying the maximum tension from the mooring lines under ULS and ALS conditions and the maximum wave [14] pressure obtained from a previous analysis using hydrodynamic and mooring analysis software. Global strength analysis was conducted using finite element method software. The SPM structure model used in this analysis is the same as the one created before for the hydrodynamic and mooring analysis. Still, the SPM model's input geometry must be solid in the finite element method software. To simplify the analysis, the chain hook on the SPM is modelled as a simple beam. Below is an image of the modelling results in the finite element method software.

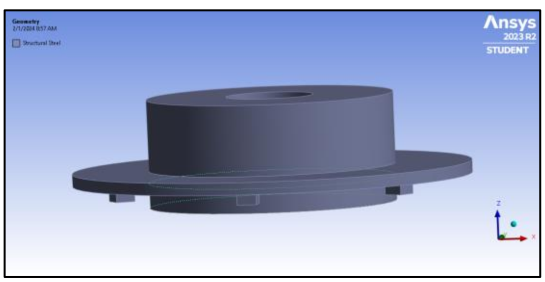


Figure 8. Structure geometry model of SPM

To apply the loading on the SPM structure, the maximum wave pressure and the maximum tension from the mooring lines under ULS and ALS conditions were used. The maximum wave pressure applied to the SPM structure is 39,727 Pa. The support of this structure is fixed and located below the buoy. Figure 9, illustrating the maximum pressure distribution on the SPM structure, is provided below.

(b)

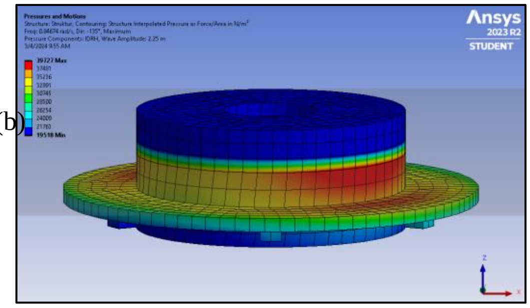


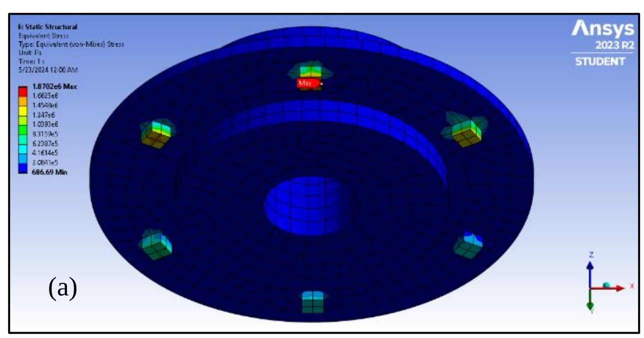
Figure 9. Maximum wave pressure on SPM structures

Then, input loading from the maximum tension value on the mooring lines for the maximum tension value used from ULS and ALS conditions and the appropriate loading on the anchor chain hook is given. The following summarises the maximum tension values on the mooring lines in ULS and ALS conditions.

Table 11. Maximum input tension value of mooring lines

| Mooring Lines | Condition | Maximum tension (kN) | Condition | Maximum tension (kN) |
|---|---|---|---|---|
| 1 | ULS | 250 | ALS | 64 |
| 2 | | 304 | (Failure | 143 |
| 3 | | 470 | of | 1001 |
| 4 | | 826 | Mooring | 1732 |
| 5 | | 956 | Line 4) | 375 |
| 6 | | 822 | | 64 |

The global strength analysis results in the maximum stress value in the SPM model structure due to the previous load input. The maximum stress result on SPM during ULS conditions occurs in the anchor hook for mooring line number 5, with a stress value of 1.87 MPa. The results of the value and location of the maximum stress in the ULS condition are shown in the following figure.



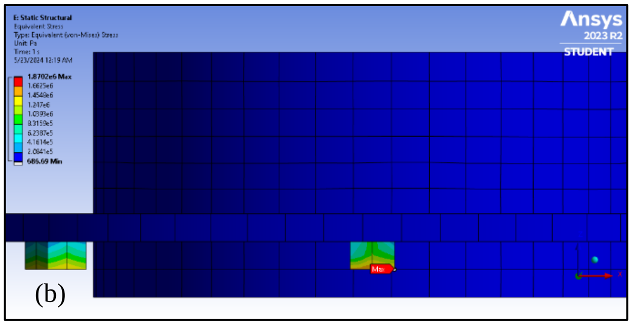



Figure 10. (a) Global stress result and (b) highest stress on SPM structures under ULS condition.

Then, the maximum stress results on SPM during ALS conditions occur in the anchor hook for mooring line number 5, with a stress value of 3.38 MPa. The results of the maximum stress value and location under ALS conditions are shown in the following figure.

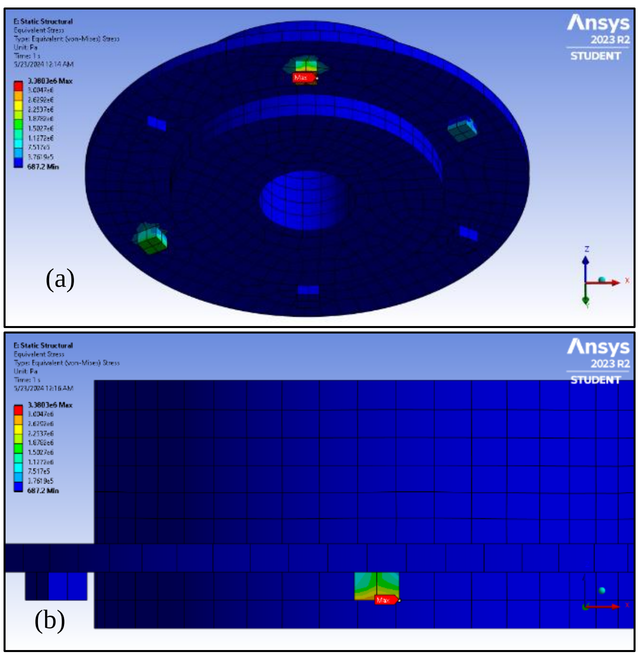



Figure 11. (a) Global stress result and (b) highest stress on SPM structures under ALS condition.

According to the standards [15], the analysis results indicate that the von Mises stress should be at most 90% of the material's yield strength. For structural steel with a yield strength of 2.5 x $10^8$ Pa, the maximum allowable stress is 225 MPa. The maximum stress on the SPM structure was 1.87 MPa under ULS conditions and 3.38 MPa under ALS conditions. These values are well below the maximum stress limit, indicating that the SPM structure's strength is robust and safe while floating with mooring lines.

## 7. CONCLUSIONS

The conclusions drawn from this research are,

1. The analysis concludes that the largest RAO values occur in surge and sway for translational motion, with a value of 7.95 m/m. The highest RAO value for rotational motion is in pitch, at 6.94 deg/m.
2. The tension analysis of mooring lines under ULS conditions showed a maximum tension of 956 kN in mooring line number 5. According to the API (2005) code, this does not exceed the allowable tension limit of 2126 kN. Under ALS conditions, the maximum tension was 1732 kN in mooring line 5 when mooring line 4 failed, which is also within the permissible limit of 2841 kN.
3. The global strength analysis of the SPM structure revealed that the maximum stresses due to wave pressure loads and mooring line tension were 1.87 MPa under ULS conditions and 3.38 MPa under ALS conditions, occurring in the chain hook of mooring line number 5. These stress values are way below the 225 MPa limit set by [2], indicating that the SPM structure is safe under extreme wave conditions with a 100-year return period.

## ACKNOWLEDGEMENTS

The authors would like to express their sincere gratitude to the Faculty of Infrastructure and Regional Technology (FTIK) for their invaluable support and funding, which enabled participation in the ISOCEEN Conference 2024 and facilitated this publication in the International Journal of Offshore and Coastal Engineering (IJOCE).

## REFERENCES

1. API, "Design and Analysis of Stationkeeping System for Floating Structures," Recommended Practice 2SK, vol. III, pp. 1-181, 2005.
2. ABS, "Safehull Dynamic Loading Approach for FPSO Systems," vol. I, 2001.
3. W. Cui, S. Fu, and Z. Hu, Encyclopedia of Ocean Engineering, Singapore: Springer, 2022.
4. H. R. Sørheim, "Analysis of Motion in Single-Point Mooring Systems," Modeling, Identification and Control, vol. 1, no. 3, pp. 165-186, 1980. https://doi.org/10.4173/mic.1980.3.2
5. A. Hamilton, "Buoy Technology," in Springer Handbook of Ocean Engineering, Springer International Publishing, 2016, pp. 937-962. https://doi.org/10.1007/978-3-319-16649-0_40
6. ABS, "Rules For Building And Classing Mobile Offshore Drilling Units," vol. I, 1989.
7. Djatmiko, Behavior, and Operability of Marine Structures on Random Waves, Surabaya: ITS Press, 2012.

8. A. W. Pradhana, Global Structural Strength Analysis of Single Point Mooring Due to Extreme Wave Loads, Bachelor Engineering Thesis: Institut Teknologi Sepuluh November, 2015.
9. Pertamina, Maintenance of Single Point Mooring (SPM), Indonesia: Pertamina, 2008.
10. Murdjito, "An Analysis on the Spread Mooring of the Belida FSO Induced by Squall Loads," Jurnal Ilmu Pengetahuan dan Teknologi Kelautan, vol. 17, pp. 15-26, 2020. https://doi.org/10.14710/kapal.v17i1.27554
11. Faltinsen, Sea Loads On Ships And Offshore Structures, 1st ed., New York: Cambridge University Press 1990, 1998.
12. Z. Adzmizah, Analysis of Mooring Buoy Sinking Using the Fishbone Diagram Method, Bachelor Engineering Thesis: Institut Teknologi Sepuluh November, 2018.
13. DNV, "Position Mooring," Offshore Standard E301, vol. I, pp. 5-73, 2004.
14. DNV, "Environmental Conditions and Environmental Loads," Recommended Practice C205, vol. I, pp. 5 - 123, 2010.
15. D. R. Mauliani, Global Structural Strength Analysis of the Buoy on the Single Point Mooring FSO Ardjuna, Bachelor Engineering Thesis: Institut Teknologi Sepuluh November, 2015.