Analysis of Mooring Line Tension in Floating Collar Net Cage

A H Adaalah¹, R W Prastianto¹, Murdjito¹, F Syalsabila¹, and M R Syarifudin¹
Department of Ocean Engineering, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia
rudiwp@oe.its.ac.id

Abstract. World fish production is increasing every year. This is mainly because of the trend to use floating net cages in aquaculture. One of the common net cage types is the collar cage. The net cage system must withstand the environmental and accidental loads, particularly on the mooring system as its function to maintain the position. Thus, this study focuses on analysis in mooring tension of the fully scaled net cage using numerical methods. The model scale data obtained from a previous experimental study and then scaled up to obtain the fully scaled net cage. After validation, current and wave data at Pangandaran bay, Indonesia is adapted to the simulation. Morison’s hydrodynamic force formula is used. Configuration of the mooring system is a rectangular array with a variation of spread angles of mooring lines between 90°, 60°, and 30°. The load cases used for simulation considering the operation and extreme conditions also the directions in lines and between lines. The result shows that the smallest mooring tension and offset is the configuration 30° in which the mooring lines spread evenly in each direction.

1. Introduction
World fish production increases every year due to the increasingly massive use of the concept of aquaculture. This is proven by the increase that reached 46.0% in 2016-2018, this value is quite large when compared to the increase that occurred in 2000 of 25.7% [1]. Aquaculture is the cultivation of aquatic animals (such as fish) and plants under controlled or semi-controlled conditions [2]. The aquaculture concept has begun to be adopted by Indonesia to support food production, especially from the fisheries sector. This is one of Indonesia’s sustainable development goals, namely to create food security and good nutrition. The media in the cultivation can use floating net cages. The type of floating net cage that is widely used and developed is the collar cage type. In general, the floating net cage system consists of three main components, including floater, nets, and mooring systems.

As a structure designed to be placed on the offshore, floating net cages are subject to environmental loads. Environmental loads that interact directly with the structure are the effects of wind, waves, and currents. Of the three influences, the most dominant is current. The proportion of effects due to currents is 70-75% of the total force on the structure, while waves play a role of 20-25% and the wind is 5-10% [3]. This can happen because the net area is the largest area of the entire structure that allows the net to capture large forces due to currents.

Environmental loads that hit the structure cause deformation and movement of the structure. To keep the structure stable at predetermined boundaries, a well-structured mooring system is needed [4]. The mechanism of the mooring system in maintaining the position of the structure is to withstand the global forces that occur on the structure. When the structure response increased, the tension that occurs in the cable will increase [5]. The mooring system is the most critical component because the failure of the mooring system can result in losses in the form of global damage [6].
Proper configuration of the mooring system can reduce the tension in the mooring line. The configuration of the mooring system that is suitable for use for floating net cages for the collar cage model is the rectangular array [7]. The mooring line spread angle is also an important thing to consider because it affects the distribution of the mooring line tension and structure offset. In addition, the determination of the angle of spread of the mooring rope can also affect the length of the mooring rope used, so that it also has an impact on the economic aspect. To find out whether a mooring system can work optimally and meet the required strength, an analysis of the mooring rope tension is needed [8]. Analysis can be done by comparing with the applicable criteria, one of which is DNVGL-OS-E301 [9]. The compared parameter is safety factor due to mooring line tension.

In conducting structural analysis, both for tension and motion analysis, the manual calculations that must be carried out to obtain the desired results are very complex. Therefore, several methods were developed to solve the analysis calculation with lowering the complexity but still acceptable, one of which is numerical modeling. The analysis of motion and force on the net using numerical modeling has been carried out [10]. Another study on the analysis of mooring line tension for floating net cages has also been carried out [11]. In both studies, a numerical model is presented which is compared with the experimental model after scaling from the original size of the floating net cage. Numerical modeling uses software for modeling and simulation.

Considering the important role of mooring systems on the global structural strength of floating net cages, an analysis of mooring line tension using numerical methods was carried out in this study. The model that is used comes from the physical experiments [12] while the modeling step refers to the numerical simulation study [13] by calculating the hydrodynamic force using the Morison equation. The validated model then scaling up using the Froude scale to be simulated according to the Pangandaran bay. The rectangular array configuration of the mooring system is used with variations of the mooring line spread angle 90°, 60°, 30°. Load cases were carried out for operation conditions and extreme conditions with In-line and Between line load directions to obtain the offset and tension of the mooring line from each configuration. The mooring line tension was then compared with the criteria to see the suitability of the line that was used.

2. Theory and Numerical Model

2.1. Morison Equation

The hydrodynamic forces that affect fixed and floating offshore structures can be calculated using the Morison equation. The requirement to use the Morison equation for the hydrodynamic force is $D\lambda < 0.2$, where $D$ is the diameter of the cylinder and $\lambda$ is the wavelength. In general, the hydrodynamic force consists of three components, namely the dynamic pressure force, the acceleration force, and the drag force [14]. The sum of the dynamic pressure force and the acceleration force is called the inertial force. Morison's equation states that the hydrodynamic forces acting on the structure consist of the inertial forces and the drag forces which are sum linearly. The hydrodynamic force that occurs is formulated in equation (1).

$$F_H = \rho \left(1 + C_M \right) A \alpha_x + \frac{1}{2} \rho C_D B \alpha_x \left| \alpha_x \right| \tag{1}$$

In the equation (1), $F_H$ is the hydrodynamic force, $\rho$ is the density of the fluid, $C_M$ is the added mass coefficient, $A$ is the cross-sectional area, $l$ is the length of the object, $\alpha_x$ is the acceleration of fluid particles, $C_D$ is the coefficient of resistance, $B$ is the longitude surface area with respect to the fluid flow, and $\alpha_x$ is the velocity of the fluid particles.

2.2. Net Equivalent

The real net has a very large number of lines. Numerical modeling of the real net is very difficult because it affects the numbers of input objects and computation time. The net modeling can be simplified using net equivalent. The main parameter of the equivalence net is the net solidity ratio and wet mass between
the real net and the numerical net that formulated in equation (2), (3), and (4) below. From this basis, the parameters of Young’s modulus, mass, and mesh geometry in the numerical model can change.

\[
S_n = 2 \frac{d_w}{l_w} - \left( \frac{d_w}{l_w} \right)^2
\]  
(2)

\[
W_{\text{wet}} = W_{\text{dry}} - F_{\text{buoyancy}}
\]  
(3)

\[
\text{Axial Stiffness} = AE
\]  
(4)

From the equation (2), \( S_n \) is the ratio of the density of the net, \( d_w \) is the diameter of the net, \( l_w \) is the length of the net. From the equation (3), \( W_{\text{wet}} \) is the wet weight of the net, \( W_{\text{dry}} \) is the dry weight of the net, \( F_{\text{buoyancy}} \) is the buoyancy force. From the equation (4), \( A \) is the cross-sectional area of the net, \( E \) is the young’s modulus net material.

2.3. Wave Field

Ocean waves are energy that propagates through a fluid medium. Waves can be generated by the wind (wind waves), the attraction of the sun and moon (tidal), volcanic eruptions, or earthquakes at sea (tsunami). Waves can be grouped into regular waves and irregular waves.

2.3.1. Regular wave.

Regular waves are a simplification with various assumptions for real waves. The simplest mathematical formulation of ocean waves is a form of sinusoidal oscillation called the Airy wave theory that has a constant period. Airy wave theory or commonly called small-amplitude wave theory explains that the assumption of wave height is very small when compared to wavelength or ocean depth.

2.3.2. Irregular wave.

An irregular wave is a superposition of several regular waves that have different frequencies and wave heights. Ocean waves have a random pattern, both in the form of elevation and propagation. For irregular wave formulations, a wave spectrum can be used, one of which is the JONSWAP spectrum. The JONSWAP spectrum has parameters that accommodate the wave characteristics of closed seas or islands. The JONSWAP spectra is formulated in equation (5).

\[
S_c (\omega) = \alpha g^2 \omega^4 \exp \left\{ -1.25 \left( \frac{\omega}{\omega_b} \right)^4 \right\} \gamma \exp \left\{ \frac{- \left( \alpha - \alpha_b \right)^2}{2 \omega_b^2} \right\}
\]  
(5)

From the equation (5)(2), \( g \) is gravity acceleration, \( \gamma \) is peakedness parameter, \( \tau \) is shape parameter. Peakedness parameter can obtained using equation (6)(7)(8), where \( T_p \) is peak wave period and \( H_s \) is significant wave height.

\[
\gamma = 5 \rightarrow if \rightarrow \frac{T_p}{\sqrt{H_s}} \leq 3.6
\]  
(6)

\[
\gamma = e^{5.75 - 1.15 \frac{T_p}{\sqrt{H_s}}} \rightarrow if \rightarrow 3.6 \leq \frac{T_p}{\sqrt{H_s}} \leq 5
\]  
(7)

\[
\gamma = 1 \rightarrow if \rightarrow 5 \leq \frac{T_p}{\sqrt{H_s}}
\]  
(8)
2.4. Numerical Model

The components of the floating net cage are modeled numerically using line objects and buoy objects at OrcaFlex software.

2.4.1. Line. Lines are flexible objects that can be used to model cables, pipes, chains, and other similar items. The line is modeled as a lumped mass consisting of a points mass (nodes) series which are joined by a massless spring (segment). Segments only model the axial and torsional properties of the line while other properties such as mass, buoyancy, and hydrodynamic forces are represented by nodes. Each node represents half the properties of the two segments connected to that node. At the last Node, the transferred properties are only half of one connected segment. The properties of the segment transferred at the node include mass, weight, buoyancy, drag, etc. A segment has axial stiffness and torsional stiffness which is represented by a combination of massless linear damper and torsional spring damper at the centre of each line segment. The effective tension at each end of the segment will have the same value. When bending stiffness is entered into the model, rotational springs and dampers at the node are included in the model. Torsional stiffness and bending stiffness are included optionally to modelling high flexible components.

2.4.2. Buoy. A Buoy is an object that can be used as a connecting point between lines. The characteristic of the buoy affects the response of the structures that are connected to the buoy. OrcaFlex has two types of buoys, namely 3D buoys and 6D buoys. The 3D buoy has three degrees of freedom that can be transferred as translational motion. While the 6D buoy has six degrees of freedom that can be transferred as translational and rotational movements. Drag force and lift force are not taken into the buoy, so the mass, volume, $C_D$, and $C_M$ of the buoy are equal to zero.

2.4.3. Froude Scale. Froude number (Fr) is a non-dimension number that describes the ratio of the squared flow velocity to the acceleration of gravity with the length of the object. The Froude number (Fr) is formulated in the equation (9), where $u$ is the velocity of the flow, $g$ is the acceleration of gravity, and $D$ is the size of the object. The Froude number can be used for scaling from model-scale to full-scale or vice versa. The similarity condition in the equation (10) must be met to be used for scaling.

$$Fr = \frac{u^2}{gD} \quad (9)$$

$$\frac{u_p^2}{gD_p} = \frac{u_m^2}{gD_m} \quad (10)$$

2.5. Line tension

Mooring line tension is a response to the restoring force on the floating structure caused by the line and its elastic properties. The elastic properties of the line are axial stiffness which is influenced by the cross-sectional area of the line and Young’s modulus of the line material. The tension that occurs on the line consist of effective tension and wall tension. The effective tension is a wall tension that has been operated with effects from external pressure due to fluid around the rope and internal pressure due to fluid in the line. While the wall tension itself is the operation of axial stiffness to elongation combined with effects due to internal and external stresses of the Poisson ratio, effects due to torsional coupling, and effects due to axial damping. The tension that occurs on the line can be formulated in equation (11) and (12) below.
\[ T_e = T_w + \left( p_o a_o - p_i a_i \right) \]  
\[ T_w = EA \varepsilon - 2\nu (p_o a_o - p_i a_i) + k_t \frac{\tau}{l_o} + EA \frac{d}{dt} \frac{l}{l_o} \]

From the equation (11), \( T_e \) is effective tension, \( T_w \) is wall tension, \( p_i \) and \( p_o \) are internal and external pressure, \( a_i \) and \( a_o \) are internal and external cross sectional stress areas. From the equation (12), \( E \) is young’s modulus material, \( A \) is cross section area, \( \varepsilon \) is axial strain, \( l \) is instantaneous length, \( \lambda \) is expansion factor, \( l_o \) is unstretched length, \( \nu \) is poisson ratio, \( k_t \) is tension or torque coupling, \( \tau \) is segment twist angle, \( c \) is damping coefficient, \( \frac{d}{dt} \) is increased length rate.

3. Methodology

In this section, the stages of this study will be explained in the form of data collection, numerical modeling, validation, initial simulation, and simulation with variations mooring line spread angles.

3.1. Data collecting

The data needed for this study includes experimental data, numerical simulation data, and environmental data. The experimental data refers to the previous research [12] which can be seen in Table 1 and Table 2. The data is used for the validation stage of the numerical model made on the experimental model due to the influence of regular wave loads.

| Description                              | Parameter | Model Scale | Full Scale |
|------------------------------------------|-----------|-------------|------------|
| Floater Diameter                         | D = 2R    | 1.5 m       | 37.5 m     |
| Net Depth                                | L         | 1.3 m       | 32.5 m     |
| Cross-sectional diameter of floater      | 2c        | 30 mm       | 0.75 m     |
| Mass per length of the floater           | \( m_f \) | 0.127 kg/m  | 79.4 kg/m  |
| Axial stiffness floater                  | \( EI \)  | 0.136 Nm²   | 1.33 x 10⁶ Nm² |
| Net solidity ratio                        | \( Sn \)  | 0.26        | 0.26       |
| Diameter of net twines                   | \( d_w \) | ≈ 0.6-0.8 mm | -          |
| Length of net twines                     | \( l_w \) | 6 mm        | -          |
| Mass of sinker in air                    | \( M_{bw} \) | 16 x 75 gr | 16 x 1172 kg |
| Spring stiffness                          | \( k_s \) | 44 N/m      | 27.5 kN/m  |
| Mass of the net cage                     | \( M_{net} \) | 357 gr (43 gr) | 5578 kg (672 kg) |

The second validation requires numerical simulation data from the previous research [13] as shown in Table 3. This validation is used to see the response to the influence of irregular wave loads. The second stage of validation still uses the previous numerical model.
Table 2. Experimental load data

| Net Solidity Ratio, Sn | Current Speed, Uc (m/s) | Regular Wave |
|-----------------------|-------------------------|--------------|
|                       |                         | Height, H (m) | Period, T (s) |
|                       |                         | 0.104        | 1             |
| 0.1                   |                         |              |               |
| 0.15                  |                         |              |               |
| 0.2                   |                         |              |               |
| 0.25                  |                         |              |               |
| 0.3                   |                         |              |               |

Table 3. Numerical simulation load data

| Current Speed, Uc (m/s) | Irregular Wave |
|-------------------------|----------------|
|                         | Significant Height, H_{1/3} (m) | Peak Period, T_P (s) | Y |
| 0                       | 0.12            | 1.8             | 3.3 |
| 0.1                     |                 |                 |    |
| 0.2                     |                 |                 |    |

Furthermore, the full-scale model is simulated according to the Pangandaran bay data which can be seen in Table 4 and Table 5. The simulation is used to obtain the configuration that produces the smallest response. The data required consists of operation conditions (10 years return period) and extreme conditions (100 years return period).

Table 4. Location data of Pangandaran bay

| Location     | Pangandaran bay |
|--------------|-----------------|
| Latitude     | 7°45’8.90”S     |
| Longitude    | 108°37’37.00”E  |
| Depth        | 45 m            |

Table 5. Environmental data of Pangandaran bay

| Parameter                        | Unit | Return Period (year) |
|----------------------------------|------|----------------------|
| Mean wind speed (1-minute)       | (m/s)| 20.6                 | 43 |
| Current speed at surface         | (m/s)| 1.03                 | 1.6 |
| Current speed at seabed          | (m/s)| -                    | 0.41 |
| Maximum wave height (H_{max})    | m    | 6.5                  | 13.4 |
| Significant wave height (H_s)    | m    | 3.5                  | 7.2 |
| Peak wave period(T_p)            | s    | 10                   | 13  |
| Mean wave period (T_m)           | s    | 5.38                 | 6.99 |

3.2. Numerical Modelling

The numerical model consists of floaters, nets, and mooring systems that are built at OrcaFlex software. The Numerical model of floater consists of a line object with Homogeneous Pipe category and 6D buoy
object. There are 32 6D buoy objects which are connected by 32 lines to form a collar frame. The 6D buoy object is used to generate a response from translational and rotational movements so that it can provide elasticity characteristics of the floater. The numerical modeling of the net is made in a net equivalence to simplify the geometry of the net. From the equivalence net, we got vertical (Nv) and horizontal (Nh) grids with a value of 10 X 32. The equivalence net consists of line objects and 3D buoy objects. There are 640 line objects in the modeling and 320 3D buoy objects. Line objects represent some of the original nets while 3D buoys are used as connecting points between lines that can respond to translational motion without having mass and volume. A total of 16 ballast are compensated as weight on the bottom 3D buoy. The configuration of the mooring system refers to a physical experiment. The mooring system consists of a bridle line and a mooring line. Numerical models are use line objects and 3D buoy objects. The endpoint on the mooring line is modeled as a fixed point. The number of objects to model the mooring system is 16 line objects and 4 3D buoy objects. The numerical model that has been created can be seen in Figure 1.

![Figure 1. Numerical Model Illustration](image)

3.3. Validation
The validation process in this study was carried out on physical experiments, numerical simulations, and the numerical model size changes.

3.3.1. Validation of numerical model-scale due to the influence of current and regular wave loads. At this stage, comparison results of the numerical model-scale simulation with experiments [12] are carried out to test the feasibility of the numerical model. Parameters that compared include drag force, net deformation, and mean tension of the fore and after mooring line. For the drag force parameter, a comparison is made at the constant current speed of 0.1 - 0.3 m/s. Comparisons for the deformation parameter of the net are only carried out for the 0.1 m/s current speed. The parameter of the mean mooring line tension carried out at 0.1 m/s current speed with 0.104 m regular wave height and 1 second period. Mean Absolute Percentage Error (MAPE) is used for the validation parameter, where the error value must be less than 5% to be considered feasible.

3.3.2. Validation of numerical model-scale due to the influence of current and irregular wave loads. The numerical model is then simulated using current loads and irregular waves with the JONSWAP spectrum to determine the response of the structure when simulated according to actual sea conditions. Simulations were carried out for 2200 seconds to calculate the required mooring line tension parameters.
The simulation results are compared with the numerical simulation [13], the parameters that are compared are the mean tension at the fore and after mooring line when given a constant current speed of 0 - 0.2 m/s and a JONSWAP spectrum wave with a 0.12 m significant wave height and 1.8 seconds period. The error value must be less than 5% to be considered feasible.

3.3.3. Validation of full-scale numerical model against model-scale. The numerical model was then scaled up using the Froude scale ($\lambda$) of 25. Therefore, the scaled-up model is called the full-scale numerical model. The scaling process is carried out for each property, object size, and configuration dimensions, including the size of the mooring line that according to the catalogue [15]. The simulation uses current loads and irregular waves from the previous stage which have been scaled. The results of the full-scale simulation are then compared with the numerical simulation using the model-scale in the previous stage to determine the difference response when the model is enlarged. The parameters that were compared are the mean tension at the fore and after the mooring line. The error value must be less than 5% to be considered feasible.

3.4. Initial Simulation
At this stage, modification of the mooring configuration is carried out to suit real conditions. Rectangular array configuration is used and the mooring lines have been taut on the seabed. In addition, a mooring buoy was added using a 3D buoy object so that the response of the structure was not so affected by the weight of the mooring line. The modified full-scale model was then simulated using Pangandaran bay data. Wind loads are not included in the calculation with the assumption that there is no part of the structure that has a large area above the water surface. Simulations are carried out for extreme conditions to obtain the mooring line tension with the load direction according to the rules [9]. From the simulation, an analysis was carried out to obtain a way to simplify the simulation that would be used for further analysis.

3.5. Simulation with variation of mooring line spread angle
After obtaining a way to simplify the simulation, the next step is to determine the variation of configuration. The configurations that are used are in the form of a mooring line spread angle (top view) $90^\circ$, $60^\circ$, and $30^\circ$. The load direction is also adjusted for each configuration. In this simulation, the structure offset and mooring line tension are generated for each configuration variation under operation and extreme conditions.

In addition, comparisons with the criteria were also carried out to check the feasibility of the mooring line. The criteria used in this study is the safety factor due to the mooring line tension from DNV GL OS E-301. The safety factor was obtained from the ratio of the minimum breaking load from a line during wet conditions with the maximum mooring line tension from the simulation. The minimum breaking load (MBL) value was obtained from the mooring line catalogue with the reference parameter in the form of mooring line diameter on a full-scale model. The value used as a comparison is a safety factor for time-domain simulation at permanent mooring type with ultimate limit state (ULS) conditions. The value of the safety factor criteria is 1.45.

4. Result and Discussion
There are 3 subsections in this result and discussion.

4.1. Validation
4.1.1. Validation of numerical model-scale due to the influence of current and regular wave loads. The comparison results of numerical simulations with experiments for the drag force parameters can be seen in Table 6. The drag force is represented by the tension of the fore mooring line [16]. In the figure, the tension for a current speed of 0.15 - 0.25 m/s is slightly different from the experimental results. While,
at the current speed of 0.1 and 0.3 m/s, the simulation results have overpredicted tension of more than 5%. However, the mean error of simulation result still gives good and acceptable results. A comparison of net deformation was also carried out in the simulation of using current load only. The net deformation that compared was taken at the time of the greatest deformation. The deformation validation was carried out qualitatively by comparing the shape of Figure 2. From the numerical simulation, it was found that the largest net deformation was at the bottom of the net is 0.5 m.

Table 6. Drag force comparison between experimental and numerical simulation

| Current Speed (m/s) | Kristiansen & Faltinsen (2014) | Simulation | Error (%) |
|---------------------|---------------------------------|------------|-----------|
| 0.1                 | 5.775                           | 6.149      | 6.47      |
| 0.15                | 10.274                          | 10.56      | 2.79      |
| 0.2                 | 13.982                          | 13.996     | 0.1       |
| 0.25                | 16.717                          | 17.099     | 2.28      |
| 0.3                 | 18.803                          | 20.278     | 7.85      |

Mean error 3.9

Figure 2. Deformation comparison between (a) experimental and (b) numerical simulation

Another parameter used to validate the simulation results numerically is the mooring line tension. In the simulation, current loads and regular waves were used to obtain the fore and after mooring line tension. The quantity that is being compared is the mean mooring line tension at a duration of 70-80 seconds from the simulation. those duration was used to obtain a constant result due to the influence of waves. The comparison results show an mean error value of 4.657% so that the model is feasible for further analysis. the comparison of quantities can be seen in Table 7.

Table 7. Mooring line tension comparison between experimental and numerical simulation

| Mooring Line         | Mean Tension | Error (%) |
|----------------------|--------------|-----------|
|                      | Kristiansen & Faltinsen (2014) | Simulation |
| Fore (Mooring line 3)| 3.95         | 4.13      | 4.655     |
| After (Mooring line 1)| -3.95       | -4.13     | 4.658     |

Mean error 4.657
4.1.2. Validation of numerical model-scale due to the influence of current and irregular wave loads. The previous numerical model was reused for comparison with the numerical study. The simulation used a current speed of 0 - 0.2 m/s and a JONSWAP wave spectrum with 0.12 m wave height and 1.8 second period. The parameter that is being compared is the mean mooring line tension at the fore and the after cage.

The comparison results can be seen in Table 8. The fore mooring line tension when there is no current load is not 0 because of the drift force due to waves. In the table, the mean error values of the fore and after mooring line tension are 2.49% and 4.14%, respectively. From these results, it is found that the numerical model is feasible to be simulated at current loads and irregular waves.

| Current speed (m/s) | Cifuentes & Kim (2017) | Simulation | Error (%) |
|---------------------|-------------------------|------------|-----------|
| 0                   | 0.372                   | 0.3577     | 3.85      |
| 0.1                 | 3.6702                  | 3.763      | 2.53      |
| 0.2                 | 7.9136                  | 7.8278     | 1.08      |

Mean error 2.49

| Current speed (m/s) | Cifuentes & Kim (2017) | Simulation | Error (%) |
|---------------------|-------------------------|------------|-----------|
| 0                   | 0.3726                  | 0.3759     | 0.89      |
| 0.1                 | 3.5406                  | 3.7629     | 6.28      |
| 0.2                 | 7.4366                  | 7.8264     | 5.24      |

Mean error 4.14

Table 8. Mooring line tension comparison between numerical simulation and present study

4.1.3. Validation of full-scale numerical model against model-scale. The numerical model of the model-scale was then scaled up with a 25 Froude scale. The model is then simulated using current loads and
irregular waves that have been enlarged according to scale. The simulation results are then compared with the simulation results of the scale model. The compared parameter is the fore and after mooring line tension. The mooring line tension at full-scale has been scaled down according to the scaling rule. The results of the comparison between the model-scale and full-scale can be seen in Table 9. From the comparison results, the mean error value is less than 5% so that the full-scale model is feasible to proceed to the next analysis stage.

4.2. Initial Simulation

4.2.1. A determination of simulation duration. The mooring system configuration on the full-scale model was modified to suit the location of the Pangandaran bay. The Modifications that occur are adding mooring buoys, adding grid lines, increasing the number of mooring ropes, and placing the ends of the mooring ropes on the seabed. The illustration of each component of the mooring system is shown in Figure 3. Determining the length of the mooring system components using several approaches. The calculation of the buoy line length and bridle line length has used a comparison that refers to the FAO reference [3]. The length of the mooring line uses an approach of 4.25 times depth while the distance of the anchor uses the Faltinsen equation [17]. The pretension is assumed to be 10% minimum breaking load (MBL) of the mooring line that used [18].

![Illustration of mooring configuration after modification. (a) side view (b) top view](image)

Analysis of the strength of the mooring system was carried out dynamically using the ultimate limit state (ULS) with an initial simulation duration of 3 hours [9]. The load direction of the initial simulation is 0° (between line 1) in extreme conditions. The simulation results for the tension parameter of the mooring line C1 can be seen in Figure 4. From the figure, a repeating pattern is obtained which indicates a repetition of the wave pattern which affects the tension of the mooring line although the magnitude can be different. Departing from this, the simulation is carried out for at least 400 seconds to get a response during one repetition period.

To reduce computational time, a cut-off can be used. The cut-off simulation aims to reduce computational time due to the influence of many objects and a high level of computational accuracy. The duration used to determine the load on the mooring line is at least 15 minutes or 900 seconds [19]. The start simulation time is when the highest wave occurs minus half the simulation duration (450 seconds). Comparison of simulations using 3 hours duration and a 900 seconds cut-off for the tension parameters of the mooring line C1 at the same time has been presented. The simulation results using the cut-off have a 0.006% Root Mean Square difference with a simulation result of 3 hours. So for the next simulation, a cut-off with a 900 seconds duration will be used.
4.2.2. A determination of load direction. The load directions that use are in-line and between-line [9]. Ideally, the load direction considered should represent the entire 360° direction, but because the structure is symmetrical, a 180° initial loading direction is used for the structure. Illustration of directional loading can be seen in Figure 5.

The simulation results for each load direction that obtained the maximum mooring line tension in a symmetrical loading direction (between line 1 with between line 3 and in-line 1 & 2 with in-line 3 & 4) showed similar results. So for further analysis, it can be simplified in the direction of loading up to 90° only (between line 1, in-line 1, in-line 2, and between line 2).

4.3. Simulation with variation of mooring line spread angle
In this study, a comparison of variations in the configuration of mooring line spread angles for floating net cages was carried out. The angle variations that used are 90°, 60°, and 30°. An illustration of the variation mooring line spread angle configuration and the load direction for each configuration can be seen in Figure 6.
Figure 6. Illustration of mooring configuration and load direction for each variation (a) configuration 90 (b) configuration 60 (c) configuration 30

4.3.1. Offset result. In the offset simulation of extreme and operation conditions, the loading direction is carried out as far as $90^\circ$ around the structure. The offset results in the form of changes in position in the direction of the X and Y axes in each direction of loading. The offset comparison can be simplified by using the resultant offsets for operation and extreme conditions as shown in Figure 7. The resultant is defined as the square root of the offset X squared added to the offset Y squared. The resultant calculation is intended to find the displacement from the starting point.

In both figures, the results show a similar pattern for the between line load direction and in-line load direction. For load direction between lines, the smallest resultant offset is found in the configuration 60. Meanwhile, for in-line direction loading, the resultant offset is obtained at the configuration 30. From these results, the largest offset results for each configuration occur in the in-line load direction. Overall,
the result of the largest offset with the smallest magnitude is in the configuration 30, this is because the offset that occurs can be held more evenly for each load direction.

4.3.2. **Mooring line tension result.** Another parameter generated from the simulation for variations in the configuration of the mooring line spread angle of 90°, 60°, and 30° under operation and extreme conditions is the mooring line tension. The results of the mooring line tension parameters are the maximum tension, significant tension, and the Root Mean Square (RMS) tension. The maximum value is used to see the largest response that occurs. The significant value is used to give the dominant value of the tension that occurs [20]. The RMS value is used to determine a more specific average value due to the effect of oscillations [21]. This is important considering that the mooring line functions as structural support due to the influence of external loads. In the simulation, time-domain analysis is used which can produce linear or non-linear values from the response of the mooring line due to the movement of the structure. A recapitulation of the results of the pulling force of the mooring line for each configuration under extreme conditions and operations is presented in Figure 8 below.

![Mooring Line Tension Parameter at Extreme Condition Simulation](image1)

![Mooring Line Tension Parameter at Operation Condition Simulation](image2)

**Figure 8.** Mooring line tension result for each configuration at (a) extreme condition and (b) operation condition

From the two figures above, the results between the maximum tension, significant tension, and RMS tension have the same trend. The configuration that produces the smallest magnitude for the three parameters of the mooring line tension is the configuration 30. This is because in the configuration 30 the pulling force of the mooring rope can be evenly distributed for the entire load direction.

4.3.3. **A comparison with mooring line tension criteria.** From the maximum tension for each configuration and condition, comparisons are made with criteria [9]. The mooring line tension then becomes the divisor for the minimum breaking load (MBL) so that the actual safety factor value is obtained. The material used for the mooring line is assumed to be nylon. When subjected to water, nylon will absorb the water and this must be considered. So, the MBL of the wet condition is taken into account. The criteria comparison is done to determine the suitability of the mooring line used. In Table 10, the comparison results with the criteria for operation and extreme conditions are obtained. These results indicate that the actual safety factor value does not meet the safety factor criteria for both extreme and operation conditions. So that the mooring line that is used in the system is not feasible to operate in the Pangandaran bay.
Table 10. Comparison mooring line tension with criteria

| DNV GL OS E301 Criteria Check |  |
|--------------------------------|---|
| Minimum Breaking Load (dry)    | 88000 N  |
| Minimum Breaking Load (wet)    | 74800 N  |
| Safety Factor                  | 1.45     |

**Extreme Condition**

| Variation         | Maximum Tension (N) | Actual SF | Required SF | Category |
|-------------------|---------------------|-----------|-------------|----------|
| Configuration 90  | 334586.53           | 0.22      | 1.45        | DANGER   |
| Configuration 60  | 307610.13           | 0.24      | 1.45        | DANGER   |
| Configuration 30  | 275066.56           | 0.27      | 1.45        | DANGER   |

**Operation Condition**

| Variation         | Maximum Tension (N) | Actual SF | Required SF | Category |
|-------------------|---------------------|-----------|-------------|----------|
| Configuration 90  | 142676.5            | 0.52      | 1.45        | DANGER   |
| Configuration 60  | 131952.56           | 0.57      | 1.45        | DANGER   |
| Configuration 30  | 121657.56           | 0.61      | 1.45        | DANGER   |

5. Conclusion

From the offset structure analysis and mooring line tension analysis that have been carried out previously, the conclusions that can be taken are:

- The validation results of the numerical model floating net cages with the physical experimental model has a mean error of 3.90% for the drag force, the deformation of the net has the same deformation and has a mean error of 4.66% for the mean tension of mooring line. Validation with the numerical model have an errors of 2.49% and 4.14% for the mean tension fore and after mooring line. The validation error meets criteria below 5% so that the model can be used for further analysis.

- The configuration that has the smallest offset in floating net cages due to the influence of waves and currents according to Pangandaran bay for extreme and operation conditions is the configuration 30. The differences in offset for extreme and operations conditions in the configuration 60 are 9.09% and 3.23%, while in the configuration 90 are 17.64% and 12.83%.

- The configuration that has the smallest maximum tension in floating net cages due to the influence of waves and currents on the Pangandaran bay in extreme and operation conditions is the configuration 30. The differences in maximum tension for extreme and operation conditions in the configuration 60 is 11.83% and 8.46%, while in the configuration 90 is 21.64% and 17.28%.

In comparison with the DNV criteria, the mooring line does not meet the requirements. From the three conclusions above, the configuration that produces the smallest response is configuration 30. When the mooring line spread angle is smaller, the mooring line tension that occurs in between line load directions is greater. Thus, further analysis is needed to obtain the most optimum mooring line spread angle when angle variation is less than 30 degrees. In addition, response analysis can be carried out if the structural system is made in groups.
References

[1] FAO, *The State of World Fisheries and Aquaculture 2020. Sustainability in action*, 2020.

[2] MAAIF, *Aquaculture Training Manual for Extension Agents in Uganda*, vol. 785. 2020.

[3] F. Cardia and A. Lovatelli, *Aquaculture operations in floating HDPE cages*, vol. 593. 2015.

[4] R. W. Prastianto, Ramzi, and Murdjito, “Mooring Analysis of SPAR Type Floating Offshore Wind Turbine in Operation Condition due to Heave, Roll, and Pitch Motions,” *IOP Conf. Ser. Earth Environ. Sci.*, vol. 618, no. 1, 2020, doi: 10.1088/1755-1315/618/1/012042.

[5] S. Junianto, Mukhtasor, R. W. Prastianto, and W. Wardhana, “Motion Responses Analysis for Tidal Current Energy Platform: Quad-Spar and Catamaran Types,” *China Ocean Eng.*, vol. 34, no. 5, pp. 677–687, 2020, doi: 10.1007/s13344-020-0061-1.

[6] I. H. Grue, “Loads on the gravity-net-cage from waves and currents,” no. June, 2014, [Online]. Available: https://ntnuopen.ntnu.no/ntnu-xmlui/handle/11250/239057.

[7] N. D. Putri, “Analisis Variasi Konfigurasi Sistem Mooring dan Olah Gerak Struktur Model Collar Cage FLoating Offshore Aquaculture Untuk Laut Lepas Indonesia,” *Tugas Akhir*, 2018, doi: 10.1017/CBO9781107415324.004.

[8] C. Cendekiawan, “Analisis Tegangan Lokal pada Swivel Multi Leg Anchor Mooring,” *Tugas Akhir*, 2017.

[9] DNVGL-OS-E301, *Offshore Standard : Position mooring*. 2018.

[10] H. Moe, A. Fredheim, and O. S. Hopperstad, “Structural analysis of aquaculture net cages in current,” *J. Fluids Struct.*, vol. 26, no. 3, pp. 503–516, 2010, doi: 10.1016/j.fluidstructs.2010.01.007.

[11] Y. Shen, M. Greco, O. M. Faltinsen, and I. Nygaard, “Numerical and experimental investigations on mooring loads of a marine fish farm in waves and current,” *J. Fluids Struct.*, vol. 79, no. 7491, pp. 115–136, 2018, doi: 10.1016/j.jfluidstructs.2018.02.004.

[12] T. Kristiansen and O. M. Faltinsen, “Experimental and numerical study of an aquaculture net cage with floater in waves and current,” *J. Fluids Struct.*, vol. 54, pp. 1–26, 2014, doi: 10.1016/j.jfluidstructs.2014.08.015.

[13] C. Cifuentes and M. H. Kim, “Hydrodynamic response of a cage system under waves and currents using a Morison-force model,” *Ocean Eng.*, vol. 141, no. February, pp. 283–294, 2017, doi: 10.1016/j.oceaneng.2017.06.055.

[14] J. R. Morison, M. D. O’Brien, J. W. Johnson, and S. A. Schaaf, “The force exerted by surface waves on piles,” *Pet. Trans AIME*, vol. 189, 1950.

[15] Survitec, *Mooring Ropes*. 2017.

[16] C. A. Cifuentes Salazar, “Dynamic analysis of cage systems under waves and current for offshore aquaculture,” *ProQuest Diss. Theses*, no. May, p. 245, 2016.

[17] O. M. Faltinsen, *Sea Loads on Ships and Offshore Structure*. Cambridge University Press, 1990.

[18] K.-T. Ma, Y. Luo, T. Kwan, and Y. Wu, “Hardware—on-vessel equipment,” in *Mooring System Engineering for Offshore Structures*, 2019, pp. 199–213.

[19] API-RP2SK, *Design and Analysis of Stationkeeping Systems for Floating Structure*, Third Edit. Washington: American Petroleum Institute, 2005.

[20] S. Junianto, Mukhtasor, R. W. Prastianto, and C. H. Jo, “Effects of demi-hull separation ratios on motion responses of tidal current turbines-loaded catamaran,” *Ocean Syst. Eng.*, vol. 10, no. 1, pp. 87–110, 2020, doi: 10.12989/ose.2020.10.1.87.

[21] A. A. Wijayanto, “Analisa Tension Pada Bagian Ujung atas Riser Akibat Vortex Induced Vibration (VIV),” no. Viv, 2016.