Strength Analysis of Offshore Aquaculture Net Structure Under Wave and Current Loads

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Abstract. One of the main problems of floating net cages when operating is the escape of fish caused by breaking or tearing of the net. This is due to the influence of environmental loads that have been studied by several researchers. However, the influence of fish on net strength has not been considered. The schooling of fish in the cage can make the hydrodynamic flow change downstream of the cage. The collision of fish in groups on the net can increase 10–28% of the environmental load received by the net. Besides, fish bites on the net reduce the net cross-sectional area and lead to axial stiffness reduction. So, this study focuses on the analysis of the net strength to determine the net maximum tension, deformation, and the location of each parameter by considering the influence of fish in the net cage. Simulations are conducted using finite element method software with cage models based on physical and numerical experiments from prior studies. The results show that the net could withstand operating conditions. Meanwhile, in extreme conditions, the net could only survive in the 0° loading direction. The largest deformation reached 2.5 times the diameter of the cage. The collision of fish in groups on the net showed that the tensile force increased significantly when adding stress loading factor. While the effect of fish bites showed that the tensile force significantly decreased on all threads with a reduction in cross-sectional area.

1. Introduction

Aquaculture is the cultivation of aquatic organisms such as fish, crustaceans, molluscs, and aquatic plants both in fresh water and in salt water. Aquaculture has been the fastest growing method of food production in the world in the last 40 years. This method has great result and increasing fishery production compared to direct capture methods [1]. It aims to improve the quality and quantity of fish production to meet the ever-increasing demand for food especially protein. Seeing this trend, developed countries such as Norway, Japan, and the United States have invented modern fisheries which use open fish farming technologies, such as floating net cages. These cages can be installed near the coast or offshore (offshore aquaculture).

This floating net cage structure is designed to withstand loads during construction and operation by considering environmental conditions and human activities in the installation area. During operation, offshore structure will receive several forces due to environmental conditions. These forces can be in the form of hydrostatic forces or hydrodynamic forces such as waves, currents, and winds. This has become the attention of researchers to analyze the hydro-structure of floating net cages with various methods, both experimental and numerical. Several researchers have performed numerical modelling with various element assumptions, hydrodynamic models, and the software used [2]–[4]. These studies show the effect of hydrodynamic loads on the movement and forces that occur in each component of the...
floating net cage. The influence of environmental loads can cause fish cage failure in mooring system, nets, and floating collars. Broken or torn nets can cause fish to escape from the floating net cages. This is the main problem in fish production during cultivation [5]. The criteria for the net failures are when the maximum tensile force that occurs in the net exceeds the parameter of the net strength (minimum mesh strength of the net material). Maximum tensile force is resulted from external loads around the net.

The influence of fish in the cages can also cause net failure. The swimming pattern of fish in the net will make combined flow patterns and currents that affect the floating net cage to be disturbed. The higher density of fish and the circular movement of fish around the net cage will result lower pressure zone at the center so there is vertical water exchange along the centerline of the net cage [6]. This can cause the drag force on the net cage to decrease significantly. Thus, the external force received by the net at the front is different from the external force received by the net at the back. Besides, the bite of fish on the net can also reduce the strength of the net. These fish bite the net to eat the biofouling attached to the net [7]. The fish bite can reduce the cross-sectional area of the net thread so that the axial stiffness of the net material is reduced.

The numerical model of floating net cages in this study is based on the physical experimental model [8] and the numerical model [4]. The floating net cage will be ideally modelled based on the main components that cause main failure in floating net cage such as floating collar, mooring system, and net. The model will be analyzed using software OrcaFlex statically or dynamically to get the effect of movement and strength of each main component of the cage. The numerical model will be fully scaled and applied to the operating and extreme conditions of Pangandaran bay. This study focuses on nets in floating net cages. Numerical modelling is used to determine the maximum tension, deformation of the net cage, and the distribution of the maximum tension of the net. The obtained result is then compared with the common parameters of the net strength, minimum mesh strength of the net material. While the deformation of the net that occurs is used to determine the volume reduction of the net cage objected to external load. This analysis was carried out on several scenarios without and with the effect of the fish behaviour in the floating net cage. The fish behaviour considered are the influence of the fish in group and the effect of fish bites.

2. Theory and Numerical Model

2.1. Hydrodynamic load

Hydrodynamic forces over the floating or fixed offshore structure commonly are calculated based on Morison equation. In fluid dynamics, Morison's equation is used to calculate the hydrodynamic force that occurs in the direction of the incoming fluid flow about the structure in the oscillating flow with the condition that \( D/\lambda \) below 0.2, \( D \) is the diameter of the cylinder and \( \lambda \) is the wavelength. In general, the hydrodynamic force consists of three components, the Froude-Krylov force (dynamic pressure), the acceleration force, and the drag force. The addition of the dynamic pressure force with the acceleration force produces a force called the inertial force. The Morison equation below is used in this study. It is the modification of the Morison equation, considering the relative velocity and acceleration between the segment and fluid flow [9].

\[
F = \frac{1}{2} \rho C_D d l [\bar{v}(t) - \bar{u}(t)] |\bar{v}(t) - \bar{u}(t)| + \rho C_M \frac{\pi}{4} d^2 l \ddot{\bar{v}}(t) - \rho (C_M - 1) \frac{\pi}{4} d^2 l \ddot{\bar{u}}(t) \tag{1}
\]

In Eq 1, \( \rho \) is the water density, \( d \) and \( l \) are the diameter and length of the segment, \( \bar{u} \) and \( \bar{v} \) are the components of particle velocity. While \( \dddot{\bar{u}} \) and \( \dddot{\bar{v}} \) are the components of particle acceleration. In this formula, \( \bar{u} \) considers superposition of current and wave orbital velocities. For the coefficient, there are inertia coefficient \( (C_M) \) and drag coefficient \( (C_D) \).

Current only, regular waves and irregular waves are conditions considered in this study. Current profile used is shear profile or the assumption that the current velocity gradually increases from the seabed to the mean sea level. Commonly, Airy wave theory is used in investigating the regular waves. Airy or small amplitude wave theory explains that the assumption of wave height is very small when compared to wavelength or ocean depth. The wave period is assumed to be a constant variable that does
The hydrodynamic forces on the mooring lines are estimated by Morison’s equation. The mooring system is modified based on Blevins wake effect [12]. The net cage [11]. Solidity ratio of the net cage for the square knotless net is defined as

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

where $d_w$ is twine diameter dan $l_w$ is twine length. $Re$ formula is similar with the floating collar, except the diameter pipe is replaced by twine diameter.

Considering the twine diameter is much smaller than the wave height, the inertia force can be neglected [12]. $C_D$ is defined based on $Re$ number and solidity ratio as shown in Eq 7. This formulation is modified based on least squares fit of numerical and experimental results [13].

$$C_D = -3,2892 \cdot 10^{-5} (Re \cdot S_n^2) + 0,00068(Re \cdot S_n^2) + 1,4253$$

There is reduced flow velocity over the downstream portion of the net that must be accounted for. So, the Blevins wake effect is taken to account as it gives a good result to model this effect in net cage [13].

2.1.3. The mooring system

The hydrodynamic forces on the mooring lines are estimated by Morison’s equation. The mooring system consists of mooring line and buoys. The buoys are floating circular cylinders, and the motions

not change with time. Then Stokes developed a second-order theory for waves that have small but finite wave heights. The second order Stokes theory is used to calculate regular wave loads.

For irregular wave, JONSWAP spectrum was used as presented below

$$S_\xi(\omega) = \alpha g^2 \omega^{-5} \exp\{-1.25(\omega/\omega_0)^{-2}\} \gamma \exp\left\{\frac{(\omega-\omega_0)^2}{2\omega_0^2}\right\}$$

where $\alpha = 0.076(X_0)^{-0.22}$ or 0.0081 if length of fetch is unknown, $X_0 = gX/U_w^2$, $X$ = length of fetch, $U_w$ = wind velocity, $\gamma$ is peakedness parameter, $\tau$ is shape parameter which 0.07 if $\omega \leq \omega_0$ and 0.09 if $\omega > \omega_0$, while $\omega_0 = 2\pi(g/U_w)(X_0)^{-0.33}$.

2.1.1. Floating collar

Wave load is the most dominant load on the floating collar. However, to get realistic conditions, the interaction forces of currents and waves were used in the analysis. Morison’s approach to calculating hydrodynamic forces on floating collar is quite general and will be used in this study.

Inertia coefficient for floating collar is achieved by considering Keulegan-Carpenter Number (KC) and Reynolds Number (Re) as shown in Eq 3 and 4. $U_c$ and $U_m$ are current and maximum wave orbital velocities, $OD$ is the pipe diameter, $v$ is seawater kinematic viscosity, and $T$ is wave period.

$$Re = \frac{(U_c+U_m)OD}{v}$$

$$KC = \frac{(U_c+U_m)\tau}{OD}$$

$C_D$ is equal to 1.2 for fully immersed cylinder, considering the $Re$ ranges between $10^4$ to $10^5$. For a floating cylinder in oscillatory flow, $C_M$ has similar trend with fully immersed cylinder, while $C_D$ is equal to half of a fully submerged cylinder [10]. So, the drag coefficient for the floater is selected as 0.6 for all conditions.

2.1.2. The net cage

The hydrodynamic approach for the net cage usually uses the Morison model or the panel model. The Morison model calculates the net as several cylinder elements. While for the screen model, the net will be divided into several panels. These two methods will calculate the drag and lift forces of each element. For this analysis, the wave effect will be considered.

The hydrodynamic load of the net follows the hydrodynamic model of the floating collar. However, there are differences in the hydrodynamic coefficients. The net hydrodynamic coefficient is determined from experimental data and depends on Keulegan-Carpenter (KC) number, Reynolds Number (Re), roughness of twine surface and net solidity ratio ($S_n$) [11]. Solidity ratio of the net cage for the square knotless net is defined as

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

where $d_w$ is twine diameter dan $l_w$ is twine length. $Re$ formula is similar with the floating collar, except the diameter pipe is replaced by twine diameter.

Considering the twine diameter is much smaller than the wave height, the inertia force can be neglected [12]. $C_D$ is defined based on $Re$ number and solidity ratio as shown in Eq 7. This formulation is modified based on least squares fit of numerical and experimental results [13].

$$C_D = -3,2892 \cdot 10^{-5} (Re \cdot S_n^2) + 0,00068(Re \cdot S_n^2) + 1,4253$$

There is reduced flow velocity over the downstream portion of the net that must be accounted for. So, the Blevins wake effect is taken to account as it gives a good result to model this effect in net cage [13].
are solved in an inertial coordinate system. There are assumed no coupling terms between the translational and rotational motions as pressure loads are dominant. Drag coefficient is assumed to be constant for simplicity with $C_D = 1.2$ [8].

2.2. Structural Model

2.2.1. Line Theory

Elements of lines is a linear flexible element used to create a model of the cable, hoses, chains, or other similar items. Lines are represented using lumped mass in software OrcaFlex. The line is modelled as a series of mass points held together by a spring massless. The point of mass being modelled is called a node while the spring connecting the nodes is called a segment. Segments only model the axial and torsional properties of the line while other properties such as mass, buoyancy, and hydrodynamic forces can be represented by nodes at the ends.

Each node represents half of the two segments which are short straight bars on either side of the node. The final node has only half of a segment on one side. Each line segment is divided into two parts and the properties (mass, weight, buoyancy, drag, etc.)

A segment has axial stiffness and torsional stiffness represented by the combination of a massless linear damper and a torsional spring damper at the centre of each line segment that applies equal and opposite effective tensions to the vertices at each end of the segment. When bending stiffness is inputed into the model, rotational springs and dampers at the vertices are included in the model. Torsional stiffness and bending stiffness are included optionally to model highly flexible components.

2.2.2. Buoy

OrcaFlex has two types of buoys, namely 3D buoys and 6D buoys. The 3D buoy has three degrees of freedom in the form of translational motion. While the 6D buoy has six degrees of freedom in the form of translational and rotational movements. The 6D buoy is used as a transfer of translational and rotational motion of the floating collar properties with specific axial stiffness and bending stiffness. Drag force and lift force are not considered on the buoy. So, the mass, volume, $C_D$, and $C_M$ buoy is equal to zero. The net cage and mooring system are modelled using line elements connected by 3D buoys. The 3D buoy only transfers linear motion, so the bending stiffness is not modelled. The bending stiffness neglected assumption applies to highly flexible materials such as polyamide and polyester.

2.2.3. Net Equivalent

The net parameters are modelled with the equivalent model so that it has characteristics that resemble the physical model of the net. The net is not modelled the same as the physical model because of the large number of elements that require longer computational time and the capabilities of the devices used. The equivalent net model still consists of a line and a buoy with three degrees of freedom. One node represents several groups of nodes in the physical net as shown in Figure 1.

Figure 1. Illustration to equivalent net

Considering the Morison approach used, it should be noted that the weight of the equivalent net must equal the weight of the original net. This can be done by modifying the Young's modulus and the mass of the numerical model. The equivalence net must satisfy the equation between the model and the physical in wet weight, and density ratio.
2.3. Influence of Fish
Fishes in floating net cages occupy up to 2.5% of the volume of net cages. This will affect the flow through and within the cages thereby affecting fish oxygen consumption, water exchange and biomass within each cage. In addition, the fish in the cage affect the hydrodynamic load on the cage, especially the net.

One type of fish behaviour response to environmental conditions and changes is fish aggregation (groups). There are several types of fish group behaviour patterns, such as Shoaling, when one or several types of fish are together in an area either temporary or permanent [12]. Schooling is a condition of a fish group that swim together in the same direction and speed. The last one is Swarm Behavior when the fishes form a group or swarming, such as shoaling, schooling, blooming. This group behaviour is used for self-defence, reproduction, and foraging. This group swimming pattern is usually done by pelagic fish such as tuna, salmon, and sardines.

The behaviour of fish swimming in groups can affect the hydrodynamic load on the net. A research conducted experimental and numerical research on the effect of groups of fish on current and wave mooring loads on collar cages with inelastic floating collars [15]. The experiment was carried out using rigid artificial fish and live fish. Experimental research using live fish with current environmental loads only shows that fish will swim in the current direction and fish will hit the back of the net in groups which can be seen in Figure 2. The study stated that the effect of the group pattern of live fish on the environmental load received by the cages increased by 10-28% from the empty net cages.

Atlantic Cod (Gadus morhua) aquaculture development is new rising industry in Norway. However, there are reports of large numbers of Atlantic cod escaping from cages. This apparently was caused by the Atlantic Cod biting the cage net, causing the net to tear, thus there are holes in the net cage net [16]. Atlantic Cod weighing 1.5 to 4.5 kg has an average mandibular tooth length of 1.8 mm with an average spacing of 3 mm. Atlantic Cod has pointed teeth with a thickness of 1 mm at the bottom while at the end it is 10 m thick. Atlantic cod teeth are 1/3 of the diameter of nylon filaments commonly used in cage nets. The research showed that the Atlantic Cod bite area at the net occurred at the bottom of the net connection with the sinker ring resulting in a hole in the net which can be seen in Figure 3.

![Figure 2. Behaviour of fish in the lower bottom of the net cage [15]](image)

![Figure 3. Net panels (a) net panels for 3 months in Atlantic Cod aquaculture cages (b) documentary when fish bite nets [16]](image)
3. Methodology

3.1. Data collection

3.1.1. Experimental data

The data used for model validation in this study are experimental and numerical data from research [4], [8]. The experiment model consisted of flexible floating collar, bottomless net, and the sinker. The detailed dimensions of the experimental model in Table 1. While the environmental load given to the experimental model is shown in Table 2. Irregular wave parameters used for validation are listed in Table 3 [4].

| Description                        | Parameter | Model scale | Full scale |
|------------------------------------|-----------|-------------|------------|
| Floating net cage diameter         | D = 2R   | 1.5 m       | 37.5 m     |
| Floating net cage draft            | L         | 1.3 m       | 32.5 m     |
| Floater cross sectional diameter   | 2c        | 30 mm       | 0.75 m     |
| Floater mass per length            | m_f       | 0.127 kg/m  | 79.4 kg/m  |
| Floater bending stiffness          | EI        | 0.136 Nm²   | 1.33 × 10⁶ Nm² |
| Net solidity ratio                 | Sn        | 0.26 & 0.32 | 0.26 & 0.32 |
| Twine diameter                     | d_w       | 0.6-0.8 mm  | -          |
| Twine length                       | l_w       | 6 mm        | -          |
| Mass of the sinker                 | m_{hw}    | 16 × 75 kg  | 16 × 1172 kg |
| Spring stiffness                   | k_s       | 44 N/m      | 27.5 N/m   |
| Mass of the net cage               | m_{net}   | 357 g       | 5578 kg    |

| Solidity ratio, Sn | Current velocity, Uc (m/s) | Wave steepness (H/λ = 1/15) |
|-------------------|---------------------------|----------------------------|
| 0.26              | 0.0                       | 0.6 – 1.6 s                |
| 0.1               | 0.6 – 1.6 s               |
| 0.2               | 0.6 – 1.6 s               |

| Current velocity, Uc (m/s) | JONSWAP spectrum parameter |
|---------------------------|----------------------------|
|                           | H_{1/3} (m) | Tp (s) | y   |
| 0.0                       | 0.12        | 1.8    | 3.3 |
| 0.1                       |             |        |     |
| 0.2                       |             |        |     |

3.1.2. Environmental data

The environmental condition considered in this study is based on Pangandaran bay, Indonesia. It is located at 7°45′8.90″S, 108°37′37.00″E with 45 meters water depth. The location is shown in Figure 4. Current condition is assumed steady. The interaction of current and irregular wave is considered. The basis data of currents and waves in Pangandaran bay are shown in Table 4.
3.2. Validation
The numerical model of this study is first validated with scaled experimental model in current only and with regular waves. Illustration for the model is shown in Figure 5. Validation is carried out based on the deformation of the net, the drag force, and the mean tension of the fore and aft mooring lines. The validation of the net deformation by comparing the simulation with the experiment results in qualitative method in 0.1 m/s current condition. The drag force is obtained from the simulation results of a model scale numerical model with a current load variation of 0.1 – 0.3 m/s. The average tension of the fore and aft mooring lines was obtained from the simulation results of a numerical model with a current load (V = 0.1 m/s) and regular waves (H = 0.104; T = 1 s). The validation parameter uses the mean absolute percentage error (MAPE) parameter as shown below:

\[
MAPE = \frac{1}{n} \sum_{t=1}^{n} \left| \frac{A_t - F_t}{A_t} \right| \times 100
\]  

(6)

where, \( A_t \) is the experimental result at time \( t \), \( F_t \) is the result of modelling at time \( t \), and \( n \) is number of data. MAPE score must be below 5%. If it does not meet these criteria, it is necessary to re-examine the numerical model based on the existing data.

The numerical model of the validated model scale will be subjected the irregular wave load based on previous research. This is done to determine the response of the motion of the numerical model according to the actual water conditions. The JONSWAP spectrum was chosen because it corresponds to the wave characteristics of closed waters or islands such as in waters. The results of the simulation in this step are the mean tension of fore and aft mooring lines.

The numerical model will then be enlarged to a Froude scale (\( \lambda \)) 25 after being validated at the previous step. This process is carried out on the dimensions and material characteristics of each component in accordance with the provisions of the Froude scale.
3.3. Global simulation
Several changes must be done to the configuration of the full-scale numerical model mooring system to suit field conditions. This is because the numerical model developed is based on a physical experimental model, where the mooring line is tied to a spring to provide pre-tension to the mooring line. The mooring system in the numerical model will be changed to catenary mooring with a rectangular array configuration type with a scattering angle of 30°. In this step, the developed floating net cage numerical model is simulated according to the characteristics of currents and waves in Pangandaran bay.

By paying attention to the wave preview in the OrcaFlex program, the duration of the numerical model simulation is reduced by using the cut off method. The simulations were conducted under extreme conditions (100-year return duration) with loading directions of 0° and 15°. The deadload taken into consideration is the weight and buoyancy of the three main structures, which are floating collars, nets, and a mooring system. Additional components, like as brackets and handrails, are not modelled globally, and are compensated for in the global analysis by the extra weight of the connectors. Error! Reference source not found. shows the nomenclature of the element model. Numbers of 1-32 show the position of the floater point from x-y plane. While, the alphabet of A until J shows the net point from x-z plane.

3.3.1. Simulation of floating net cage due to currents and waves in Pangandaran bay in extreme and operating conditions.
In this step, the developed floating net cage numerical model is simulated according to the characteristics of currents and waves in Pangandaran bay. Simulations were reviewed under operating conditions (10-year environmental database) and extreme conditions (100-year environmental database). The simulation results in this process are the tension that occurs in each element of the line(line)or thread webs such as time history (table). Not only that, the movement of each node of the net in the x, y, and z directions is also needed to see the deformation of the net that occurs and the reduction in the volume of the cage. The data is obtained from the time history of the x, y, and z positions of the 3D buoy or net node.
3.3.2. Simulation of floating net cage with variations of fish schooling

Floating net cage is simulated to see the effect of fish schooling. The schooling of fish is assumed to be the Stress Loading Factor (SLF) of the cage net. Fish in cages can affect 10-28% greater environmental load when compared to empty cages [15]. This is due to the influence of fish in groups at the back of the net (in the direction of the current). Thus, the variation of stress loading factor given is 1.10 and 1.28. The simulation results obtained are the maximum tension of each line element and the x, y, z coordinates of each 3D buoy in the form of time history. Detailed model for simulation is illustrated in Figure 7.

3.3.3. Simulation of floating net cage with variations of fish bite

The numerical model of floating net cage is simulated by providing variations in fish bites. Fish bites are assumed to reduce the cross-sectional area of the net thread by 25% and 50%, respectively. Reducing the cross-sectional area of the twine will reduce the axial stiffness of the web material so that it affects the strength of the web. The simulation results obtained are the maximum tension of each line element and the x, y, z coordinates of each 3D buoy in the form of time history. Detailed model for simulation with the effect of fish bite is illustrated in Figure 8. The simulation results obtained are the maximum tension of each line element and the x, y, z coordinates of each 3D buoy in the form of time history.

Figure 7 Floating net cage model with detailed area of given safety loading factor for simulation

Figure 8 Floating net cage and the area of fish bite for simulation

4. Results and Discussion

4.1. Validation

The floating net cage structure model was validated under current only, interaction current-regular waves, current-irregular waves interaction, and validation from model scale to full scale. At current loads only, the drag force that occurs in the net due to constant current loads is equal to the tension in
the front mooring line. It is because the tension in the front mooring line represents the global force of the structure [17]. Deformation validation is done qualitatively. Under current conditions and regular, irregular waves, and a comparison from the model scale to the full scale, the tension in the fore and aft mooring lines will be seen.

Table 5 show the comparison of experimental results by with numerical simulations. The numerical simulation results are not much different at the current velocity of 0.10-0.25 m/s. However, at a speed of 0.3 m/s, the numerical simulation results are higher than the experimental results with an error of 7.85%. In this condition, the model predicts the result of the drag force which is higher than it should be. There needs to be further improvements in hydrodynamic modeling, especially the resistance coefficient equation for the case with higher currents.

Overall, the numerical model is still acceptable because it has an average error of less than 5%. Considering the flexibility of the net, it is necessary to look at the deformation that occurs to ensure that the floating net cage model meets the requirements. In Figure 9, the left shows the results of the physical experiment [8] while on the right shows the simulation maximum deformation results. Validation was carried out qualitatively by comparing the two visual results. The numerical result already has a deformation shape that resembles the results of physical experiments. The largest deformation of the net reaches 0.5 meters at the front of the floating net cage model.

![Figure 9 Deformation of the floating net cage in experiment (left) [8] and simulation (right)](image)

| Current Speed (m/s) | Drag Force (N) | Error (%) |
|---------------------|---------------|-----------|
|                     | Experiment [8]| Simulation|
| 0.10                | 5.775         | 6.149     | 6.47 |
| 0.15                | 10.274        | 10.560    | 2.79 |
| 0.20                | 13.982        | 13.996    | 0.10 |
| 0.25                | 16.717        | 17.099    | 2.28 |
| 0.30                | 18.803        | 20.278    | 7.85 |

Mean error 3.90

| Mooring Line       | Mean Tension | Error (%) |
|--------------------|--------------|-----------|
| Fore (Mooring line 3) | 3.95         | 4.13      | 4.655 |
| After (Mooring line 1) | -3.95       | -4.13     | 4.658 |

Table 6 Validation result for current and regular waves

Mean error 4.657

The results for simulations with current and regular wave loads, in terms of the average mooring tension on the front and rear of the floating net cage model. The duration taken is the last 10 seconds by
considering the stable simulation conditions. The error obtained is 4.657% so that the model is validated. The comparison of simulation and experimental results can be seen in Table 6. The simulation results are validated by numerical results [4] which also use the same model and environmental parameters. Obtained for the condition of current and irregular waves load, the model can be trusted with the error shown in Table 7. For zero current, the tension in the front and back when the difference is not equal to zero. This is due to the force drift due to waves on the cage.

Table 7 Validation result for current and irregular waves

| Current speed (m/s) | Previous numerical study [4] | Simulation | Error (%) |
|---------------------|-------------------------------|------------|-----------|
| 0.0                 | 0.3720                        | 0.3577     | 3.85      |
| 0.1                 | 3.6702                        | 3.7630     | 2.53      |
| 0.2                 | 7.9136                        | 7.8278     | 1.08      |
| Mean error          |                               |            | 2.49      |

Table 8 Validation result between model and full scale

| Current speed (m/s) | Previous numerical study [4] | Simulation | Error (%) |
|---------------------|-------------------------------|------------|-----------|
| 0.0                 | 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      |

Once the model scale has been validated, it is necessary to convert the model to a full scale that approximates the size of the general cage in open waters. The geometry is enlarged to a scale of 25 times and other parameters follow the provisions of the Froude scale. The results of the tension of the full-size mooring line are scaled down and then compared with the results of the model sizes as shown in Table 8.

4.2. Net Strength in Current and Waves
The simulations were conducted for operation and extreme condition with the loading direction of 0°, 15°, 30°, and 45°. The calculation time needed was 900 seconds. The simulation results generated from time domain data which tend to have noise data. So, the parameter that used in the net strength analysis as the significant tension. Net strength analysis was done by comparing the significant tension of every twine with minimum mesh strength. The parameter was obtained from tension test of the net sample. Both of the end tips of net were pulled with specific load until the net was torn. Net strength parameter used is equivalent minimum mesh strength based on [18]. The water absorption of net was considered which reduced the minimum mesh strength up to 15%.
Table 9 Comparison between maximum significant tension of the net element and the minimum mesh strength under operation load condition

| Condition | Load Direction (°) | Maximum Significant Tension (kN) | Minimum Mesh Strength (kN) | Category |
|-----------|--------------------|----------------------------------|--------------------------|----------|
| Operation | 0                  | 26.48                            | 34.14                    | SAFE     |
|           | 15                 | 28.88                            | 34.14                    | SAFE     |
|           | 30                 | 28.05                            | 34.14                    | SAFE     |
|           | 45                 | 28.43                            | 34.14                    | SAFE     |

In operation conditions, the highest significant tension in each load direction is in the 15° load direction. This is because the projected cross-sectional area of the net is exposed to more environmental loads than the other load directions. When the load direction is 15°, the position of the front and back net twine do not cover each other so that the force received by the front net twine is almost the same. Details of the strength analysis data on the net due to currents and waves operating conditions can be seen in Table 9. From the table, the net still can survive in operation conditions in each direction of loading.

Table 10 Comparison between maximum significant tension of the net element and the minimum mesh strength under extreme load condition

| Condition | Load Direction (°) | Maximum Significant Tension (kN) | Minimum Mesh Strength (kN) | Category |
|-----------|--------------------|----------------------------------|--------------------------|----------|
| Extreme   | 0                  | 32.89                            | 34.14                    | SAFE     |
|           | 15                 | 42.55                            | 34.14                    | DANGER   |
|           | 30                 | 50.66                            | 34.14                    | DANGER   |
|           | 45                 | 47.22                            | 34.14                    | DANGER   |

The highest significant tension in each load direction occurs in the 30° load direction for extreme conditions. This is because the projected cross-sectional area of the net twines is exposed to more environmental loads than the other load directions. This is also influenced by the very large movement of the cage during extreme conditions so that when the loading direction is 30° the projected cross-sectional area of the net twine exposed to the direct environmental load is more. Detailed data on the strength analysis on the net due to currents and waves operating conditions can be seen in Table 10. From the table, the net failure is in the loading direction of 15°, 30°, and 45°. This is because the highest significant tension in each load direction is above the minimum mesh strength of the net material.

Analysis of the maximum deformation that occurs in the net is carried out by looking at the largest volume reduction in the cage net at each time. The data needed to calculate the volume reduction are the x, y, z positions each time at the marker point A1, A9, A17; E1, E9, E17; J1, J9, J17. Volume reduction due to deformation to get volume reduction each time. The results of these calculations obtained the time when the largest volume reduction occurred. So that the position of x, y, z at the marker point is to obtain the maximum deformation of the net.

The calculation results of the volume reduction in the floating net cages due to currents and operating conditions obtained the time when the largest volume reduction occurred for every loading direction. Then the movement of the marker point at that time is plotted on a graph and compared with the original condition of the net, it can be seen for the direction of operating conditions in Figure 10. The figure shows that the midpoint of the floating net cage every load direction. The largest deformation occurred in simulation with 0° load direction which is 47.06 m or equal to 1.25 cage diameter, the 15° load direction is 45.50 m or equal to 1.21 cage diameter, the 30° load direction is 40.50 m or equal to
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4.3. Net Strength in Current, Waves, and the Effect of Fish Schooling

The simulation results are then analyzed for the strength of the net in the area that given the stress loading factor (SLF). These results were compared with the equivalent minimum mesh strength and significant tension in operation conditions without stress loading factor (SLF). The simulation results in the form of significant tension on each vertical and horizontal twine scenario of current and wave variations of SLF with a 15° load direction in operating conditions indicate that the horizontal twine with SLF 1.28 has a greater tension than the horizontal twine with SLF 1.10. However, the vertical twine tension with two variations SLF is almost the same. This is caused by the influence of the floater and the mooring system as the transfer of the tension that occurs due to the environmental load received by the net. So SLF has more influence on horizontal twine only. The largest significant tension on net twine with SLF 1.10 is 29.34 kN on A9 vertical twine while in SLF 1.28 twine is 29.45 kN on A9 vertical twine.
The significant tension on the vertical and horizontal twines increased when applying SLF of 1.10 and 1.28 to the net twines. Tension at vertical twine with SLF 1.10 increased by 0.464 kN or 464 N while vertical twine with SLF 1.28 increased by 0.565 kN or 565 N. Tension at horizontal twine with SLF 1.10 increased by 0.066 kN or 66 N while horizontal twine with SLF 1.28 increased by 0.280 kN or 280 N. Detailed data on the analysis of the strength of the net due to currents and waves with variations in SLF can be seen in Table 11. From the table, the net still can survive or not fail under operating conditions with additional SLF variations in some net twines. This is because the highest significant tension on vertical and horizontal twine is still below the minimum mesh strength of the net material.

Table 11 Comparison between the significant tension of the simulation considering the influence of fish in groups with the minimum mesh strength

| Twines Position | Load Case | Significant Tension (kN) | Minimum Mesh Strength (kN) | Category |
|-----------------|-----------|--------------------------|---------------------------|----------|
| Vertical Twines | Operation | 28.88                    | 34.14                     | SAFE     |
|                 | SLF 1.10  | 29.34                    | 34.14                     | SAFE     |
|                 | SLF 1.28  | 29.45                    | 34.14                     | SAFE     |
| Horizontal Twines | Operation | 9.83                     | 34.14                     | SAFE     |
|                 | SLF 1.10  | 9.9                      | 34.14                     | SAFE     |
|                 | SLF 1.28  | 10.11                    | 34.14                     | SAFE     |

4.4. Net Strength in Current, Waves, and the Effect of Fish Bite

The data obtained is processed to obtain the significant tensile force in each net twine. The result showed that the reduction in the diameter of the vertical and horizontal threads can affect the tension of the twine. This is caused by the influence of environmental loads on the cross-sectional area of the net twine. Environmental loads have a considerable influence on the tension that occurs in the net. The smaller the projection area exposed to environmental loads, the smaller the drag force that occurs in the twine. In addition, the cross-sectional area also affects the stiffness of the twine element. The smaller the cross-sectional area of the element, the smaller the stiffness of the element so that the internal pressure on the element is getting smaller.

Table 12 Comparison between the significant tension of the simulation considering the influence of fish bite with the minimum mesh strength

| Twine element | Net volume reduction | Significant Tension (kN) | Minimum Mesh Strength (kN) | Category |
|---------------|----------------------|--------------------------|---------------------------|----------|
| HorizontalI1  | 0%                   | 0.87                     | 34.14                     | SAFE     |
|               | 25%                  | 0.70                     | 34.14                     | SAFE     |
|               | 50%                  | 0.63                     | 34.14                     | SAFE     |
|               | 0%                   | 0.64                     | 34.14                     | SAFE     |
| HorizontalJ1  | 25%                  | 0.55                     | 34.14                     | SAFE     |
|               | 50%                  | 0.51                     | 34.14                     | SAFE     |
|               | 0%                   | 12.36                    | 34.14                     | SAFE     |
| VerticalJ1    | 25%                  | 12.33                    | 34.14                     | SAFE     |
|               | 50%                  | 12.32                    | 34.14                     | SAFE     |
|               | 0%                   | 3.16                     | 34.14                     | SAFE     |
| VerticalJ2    | 25%                  | 2.16                     | 34.14                     | SAFE     |
|               | 50%                  | 0.66                     | 34.14                     | SAFE     |
Detailed data on the analysis of the strength of the net due to currents, waves, and the effect of fish bites in the direction of loading at 15° operating conditions can be seen in Table 12. From the table, the net still survives on the net threads given the diameter reduction treatment. This is because the highest significant tensile force on the twine is still below the minimum mesh strength of the net material. However, this analysis only considers each twine tension at the ends of the twine without considering the geometric differences between twine.

5. Conclusion
From the process of study results, calculations, simulations, and discussions that have been carried out, the following conclusions can be summarized from this research:

1. The results of the validation of the numerical model of floating net cages with the physical experimental and the numerical model show that the average error of all validation parameters meets the validation criteria below 5% so that the developed floating net cage numerical model can be analyzed further.

2. The simulation of the floating net cage numerical model due to the influence of currents and waves on floating net cages in Pangandaran bay shows that the largest significant tension of net occurs in operating load conditions with the direction of 15° and 30° in extreme conditions. The results of the strength analysis show that the net can still withstand operating conditions in each direction of loading. Meanwhile, in extreme conditions, the net can survive only in the 0° loading direction. The biggest deformation in operating conditions at 0° loading direction equal to 1.25 times cage diameter. While the largest deformation in extreme conditions with loading direction of 15° is 2.50 times cage diameter.

3. The simulation results of the floating net cage numerical model due to currents, waves, and the influence of fish in Pangandaran bay operating conditions showed that the significant tension of the twine increased when safety load factor of 1.10 and 1.28 were given. The results of the analysis showed that the net was safe under influence of fish in operating load conditions.

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