Mooring Design Selection of Aquaculture Cage for Indonesian Ocean

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Abstract. Fish production is important for the economy in fishing community and for ensuring food security. Climate change will lead a threat to fish productivity. Therefore, a solution offered is to cultivate certain fish, especially those with high economic value by using offshore aquaculture technology. A Sea Station cage is one of the offshore aquaculture cage model that has been used in some locations. As a floating structure, the Sea Station cage need a mooring system to maintain its position. This paper presents the selection analysis of the mooring system designs of the Sea Station cage model that it is suitable with Indonesia Ocean. There are 3 mooring configurations that are linear array, rectangular array, and 4 points mooring type. The nylon mooring rope type has been selected to be used on the 3 mooring configurations and the rope has a diameter of 104 mm with a breaking force of 2.3 MN. Based on results from comparing the 3 mooring configurations, the best mooring configuration is linear array with the tension on the rope of 217 KN and has the safety factor of 0.2 based on DNVGL OS-E301

1. Introduction

Fish production from aquaculture technique Indonesia is 2% of total fish supply worldwide. Based on climate zones, Indonesia occupies the first position of the largest potential of marine products from aquaculture. Vietnam as a fellow Southeast Asian country with a smaller potential of marine products, has twice the production of larger than Indonesia [1]. Therefore, the development of offshore aquaculture is very important to be implemented in Indonesia.

One form that has been developed in the United States is the Sea Station cage. The Sea Station system has also been developed by Ocean Spar Technologies[2]. The structure of this building consists of a spar and a wire connected with a steel cable at 6, 8,10 or 12 sides. This structure can be placed half-afloat in the waters with a quiet environment. In the ferocious sea conditions this structure is drowned entirely about 15 meters below sea level. This structure has been used more than 50 units in the world. The Sea Station cage has a motion response due to the influence of the environmental load. The design of mooring system for offshore aquaculture is as important part of the main system because environment condition in open sea quite strong. So that this research aims to analysis and selection of the mooring system for the Sea Station cage. There are 3 mooring configurations that is analyzed in this research: a) linear array, b) rectangular array, and c) 4 points mooring type

2. Basic Theory

2.1 Aquaculture
Aquaculture is the cultivation of marine biota in a system that is controlled by humans. Ecosystems in aquaculture are made in such a way as to resemble the native habitat of marine biota cultivated. Aquaculture consists of several methods one of which is the open-net method. Offshore aquaculture offers many environmental benefits, and relative to other forms of animal protein production, the offshore aquaculture is an attractive option for expanding production [8]. The aquaculture structures must be integrated to accommodate a variety of needs such as automated food systems, protective nets from predators, and a dividing system for dead fish [3]. Besides, selection of the aquaculture cage location must be quite far from the shipping lanes and other structure in ocean. For example, the aquaculture cage cannot be installed in the Madura Strait is one of the busiest shipping lanes in Indonesia and many subsea pipeline has been installed in the Madura Strait [11].

Open-net method or open floating net is indeed still controversial because marine biota are cultivated directly interact with the environment. In some cases residues from aquaculture can contaminate the sea especially in closed waters but applications for high seas have a great potential for food security from marine resources.

2.2 Sea Station Cage

Sea Station cage is a offshore aquaculture structure that adopts the Single Point Anchor Reservoir (SPAR) offshore building [2]. The center of this structure is small SPAR and is connected to a ream using a steel cable on its side. This structure includes a simple and economical form. The structure of this model has advantages of relatively cheap construction costs. This form proves to be capable of being either submerged, or semi submerged. The source condition is usually applied to deep waters to reduce malignant ocean wave energy. Illustration of the structure model can be seen in Figure 1.

![Image of Sea Station Cage](image)

**Figure 1.** Sea Station Cage [2]

2.3 Aquaculture Mooring Configuration

With the development of aquaculture technology into the deep sea, the practice of mooring system commonly used on aquaculture technology is also growing. The mooring system configuration should be stable and reliable for a variety of offshore aquaculture structures. This mooring system also facilitates the installation of feeder systems and harvesting systems [4]. Analysis of the aquaculture is certainly not independent of the mooring system. Offshore aquaculture structures must take into account the effects of ocean waves and currents. Based on Finite Element Analysis (FEA) analysis, the nonlinear component of current and wave has an effect of up to 13% [9].

Here are some commonly mooring configurations that are the 3 mooring configurations: a) linear array, b) rectangular array, and c) 4 points mooring type. The mooring configuration model as illustrated in Figures 2, 3 and 4.
a) Rectangular Array Type

![Rectangular Array Type Diagram]

**Figure 2.** Rectangular array mooring configuration

b) Linear Array Type

![Linear Array Type Diagram]

**Figure 3.** Linear array mooring configuration

The characteristics of this type of mooring configuration are as follows:

a) High efficiency on multi-cages installation
b) Tolerance towards current from different direction
c) Local failure will have major effect on mooring grid system integrity
d) High risk of disease spreading in fish cage and fish residue concentration

c) Independent 4 Points Mooring Type

![Independent 4 Points Mooring Type Diagram]

**Figure 4.** Independent 4 Points Mooring Type

Main characteristics of this mooring configuration present as follows:

a) High efficiency when two-directional current occur towards the mooring system
b) Minor integrity effect when failure occur in single cage
c) One of the most expensive mooring configuration in installation

2.4 JONSWAP Wave Spectrum

The wave spectrum used in this final project is the JONSWAP spectrum. The JONSWAP spectrum equation is a modification of the Pierson-Morkowitz spectrum equation that is adapted to existing
marine conditions. The JONSWAP spectrum equation according to Djatmiko (2012) [6] can be written according to Equation (1).

\[ S(\omega) = \alpha g^2 \omega^{-5} \exp \left[ -1.25 \left( \frac{\omega}{\omega_0} \right)^{-4} \right] \gamma \exp \left[ \frac{(\omega - \omega_0)^2}{2\tau \omega_0} \right] \]

where:
- \( \alpha = 0.0076 \left( X_0 \right)^{0.22} \)
- \( X_0 = gX/U_w^2 \)
- \( X \) = fetch length (m)
- \( \alpha \) = fetch, 0.0081 if the fetch length is unknown
- \( \gamma \) = peakedness parameter, the value vary from 1.0 up to 7.0.
- \( \tau \) = shape parameter
- \( \tau = 0.07 \) for \( \omega \leq \omega_0 \)
- \( \tau = 0.09 \) for \( \omega \geq \omega_0 \)

The following is a spectrum JONSWAP derivative equation that uses significant wave height input and period. The equation can be seen in Equation (2) [5].

\[ S(\omega) = 155 \left( \frac{X_o^2}{T_{\text{rms}}^4 m^4} \right) \exp \left( -\frac{944}{T_{\text{rms}}^4 \omega^4} \right) \gamma^\omega \]

**2.5 Response Amplitude Operator (RAO)**

Response-Amplitude Operator (RAO) is a response function that occurs due to waves in the frequency range of the structure. The result of RAO is used to estimate the motion response of structure due to wave load [6]. The formulation of RAO for translation motion i.e. surge, sway, and heave present as equation (3):

\[ \text{RAO} = \frac{\zeta_k}{\zeta_0} (\text{m/m}) \]

The RAO for rotation motions is the ratio between the amplitude of the rotational motion and the wave inclination. The formulation of RAO for rotational motion i.e. roll, pitch, and yaw present as equation (4) [6]:

\[ \text{RAO} = \frac{\dot{\zeta}_k}{k_\omega \zeta_0} = \frac{\dot{\zeta}_k}{\omega^2 / g \zeta_0} (\text{rad/rad}) \]

Where:
- \( g \) : acceleration of gravity
- \( \omega \) : wave frequencies
- \( \zeta_0 \) : amplitude of structure motion
- \( \dot{\zeta}_0 \) : amplitude of wave motion

**2.6 Irregular Wave Motion Response**

A response spectrum of floating structure is the result of interaction between RAO with wave spectra. A response spectrum is simply a plot of the peak or steady-state response of a series of oscillators of varying natural frequency. The resulting plot can then be used to pick off the response of any linear system, given its natural frequency of oscillation. The formulation of response spectrum of floating structure in an irregular wave presents as equation (5)[6]:

\[ S_{\zeta}(\omega) = \text{RAO}^2 \cdot S_{\zeta}(\omega) \]

Where: \( S_{\zeta}(\omega) \) : Spectra of the response and \( S_{\zeta}(\omega) \) : Wave spectrum
2.7 Mooring Tension

The environmental loads acting on the structure cause tension to mooring line. There is relationship between the mooring offset and the mooring tension. The mooring tension can be estimated using numerical modeling. Regarding with recommendations of DNV GL OS-E301, then the characteristic Strength, $S_C$, is estimated from the minimum breaking strength $S_{mb}$ of new components, as equation (6):

$$S_C = 0.95 \, S_{mb}$$ (6)

The mooring lines are considered to be intact in the analysis of the Ultimate Limit State (ULS) [7]. The design equation for the ULS is given by equation (7) [7]

$$S_C - T_{C-mean} \, \gamma_{mean} - T_{C-dyn} \, \gamma_{dyn} \geq 0$$ (7)

The design equation of utilization factor, $U$, presents as equation (8) based on the recommendations of DNV GL OS-E301 [7]. The utilization factor, $U$, of the mooring system is the comparison between the actual mooring line tension with the mooring line capacity.

$$U = \frac{T_{C-mean} \, \gamma_{mean} + T_{C-dyn} \, \gamma_{dyn}}{S_C} \text{ where } U \leq 1$$ (8)

Where
- $T_{C-mean}$: Mean tension of the time series
- $T_{C-dyn}$: TMPM - $T_{C-mean}$
- $T_{MPM}$: Most probable max of the time series
- $S_C$: Characteristic Strength of mooring line
- $\gamma_{mean}$: Partial safety factor on mean tension
- $\gamma_{dyn}$: Partial safety factor on dynamic tension

The partial of the safety factor for mean and dynamic tension can be seen in Table 1 [7].

| Consequence Class | Type of analysis of wave frequency tension | Partial Safety Factor on mean tension $\gamma_{mean}$ | Partial Safety Factor on dynamic tension $\gamma_{dyn}$ |
|-------------------|----------------------------------------|-----------------------------|-----------------------------|
| 1                 | Dynamic                                | 1.10                        | 1.50                        |
| 2                 | Dynamic                                | 1.40                        | 2.10                        |
| 1                 | Quasi-static                           | 1.70                        |                             |
| 2                 | Quasi-static                           | 2.60                        |                             |

3. Data Collection

3.1 Environmental data

In this research, the environmental data uses Timor Sea data. The wave characteristics used in the analysis such as Table 2.

| Data of wave (100 years)          |          |
|-----------------------------------|----------|
| Wave height                       | $H_s = 4.8 \, m$ |
|                                   | $T_p = 11.5 \, s$ |
|                                   | $T_z = 8.3 \, s$ |

| Wave velocity (10 years)          |          |
|-----------------------------------|----------|
| Current                           | 1.1 \, m/s |
3.2 Structure data
The structure data of Sea Station Cage is presented as in Table 3. As important as the structural weight, there is also support system weight that contributes to the cumulative weight as shown in Table 4.

**Table 3. Structural dimension and weight of Sea Station**

| Components     | Length (m) | Inner diameter (m) | Outer diameter (m) | Number | Weight (ton) |
|----------------|------------|--------------------|--------------------|--------|--------------|
| SPAR           | 11.06      | 0.98               | 1.00               | 1      | 3.45         |
| Rim Section    | 6.53       | 0.39               | 0.40               | 8      | 2.45         |
| Sling          | 9.32       | -                  | 0.02               | 16     | 2.38         |
| Flange         | 0.05       | 1.00               | 1.50               | 2      | 0.36         |
| **Total of weight** |           |                    |                    |        | **8.65**     |

**Table 4. Support system of Sea Station cage**

| Items               | Weight (ton) |
|---------------------|--------------|
| Fish feeding        | 2.00         |
| Live load (workers) | 0.20         |
| Net of cage         | 0.30         |

3.3 Mooring Line Sizing
The mooring line uses the type of the nylon mooring rope. The nylon rope characteristics used in the analysis such as Table 5[10].

**Table 5. Properties of mooring line [10]**

| Diameter (mm) | Mass in air (kg/m) | MBL in wet (kN) |
|---------------|---------------------|------------------|
| 104           | 6.7                 | 2310             |

4. Analysis

4.1 Structural Modeling
Modeling of structure is carried out using numerical modeling software. The modeling of the net is performed by simplified model with considering the same weight as the actual net weight. The modeling of structure and net is presented as Figure 5.

**Figure 5. Structural modeling**

4.2 Mooring Configuration Modeling
The mooring line configuration analysis is performed using numerical modeling software. This research uses some commonly mooring configurations that are the 3 mooring configurations: a) linear
array, b) rectangular array, and c) 4 points mooring type. The rectangular array configuration is modeled as shown in Figure 6. The linear array configuration is modeled as shown in Figure 7. The model with 4 points mooring configuration is done as in Figure 8.

Figure 6. Rectangular array mooring configuration modeling

Figure 7. Linear array mooring configuration modeling

Figure 8. The 4 points mooring configuration modeling

4.3 Hydrodynamic Response
The response spectrum of a floating structure is the result of interaction between RAO with wave spectra. The response spectrum of the sea station cage moored is estimated by multiplication of the RAO quadrated with irregular wave spectrum. Here, the wave spectrum uses JONSWAP Spectrum. The analysis of the response spectrum of the sea station cage is carried out by numerical modeling. The result of the response spectrum of the rectangular array mooring configuration in translation motion for wave direction 0 degree is presented as Figure 9.
Figure 9. Response spectrum of the rectangular array configuration for wave direction 0 direction (translation motion)

The result of the response spectrum of the linear array mooring configuration in translation motion for wave direction 0 degree is presented as Figure 10.

Figure 10. Response spectrum of the linear array configuration for wave direction 0 direction (translation motion)

The result of the response spectrum of the 4 points mooring configuration in translation motion for wave direction 0 degree is presented as Figure 11.

Figure 11. Response spectrum of the 4 points mooring configuration for wave direction 0 direction (translation motion)

The result of the response spectrum of the rectangular array mooring configuration in rotation motion for wave direction 0 degree is presented as Figure 12.
The result of the response spectrum of the linear array mooring configuration in rotation motion for wave direction 0 degree is presented as Figure 13.

The result of the response spectrum of the 4 points mooring configuration in rotation motion for wave direction 0 degree is presented as Figure 14.

4.4 Tension and Offset Analysis
The analysis of the tension and maximum offset of the mooring line is carried out by numerical modeling. The results of the tension and maximum offset for the rectangular array mooring configuration in translation motion is presented as Table 6.
Table 6. The results of tension and offset for the rectangular array mooring configuration

| Heading | 0     | 45    | 90     |
|---------|-------|-------|--------|
|         | Tension (N) | Tension (N) | Tension (N) |
| Cable 1 | 94.167 | 168.121 | 8.973  |
| Cable 2 | 6.837  | 159.781 | 70.165 |
| Cable 3 | 9.987  | 9.916  | 7.072  |
| Cable 4 | 75.045 | 29.587 | 40.186 |
| Cable 5 | 8.658  | 24.765 | 13.894 |
| Cable 6 | 61.167 | 290.606 | 69.414 |
| Cable 7 | 14.091 | 33.832 | 100.238 |
| Cable 8 | 73.750 | 7.601  | 7.660  |
| Offset (m) | 6.978  | 3.826  | 2.243  |

The results of the tension and maximum offset for the linear array configuration in translation motion is presented as Table 7.

Table 7. The results of the tension and maximum offset for the linear array configuration

| Heading | 0     | 45    | 90     |
|---------|-------|-------|--------|
|         | Tension (N) | Tension (N) | Tension (N) |
| Cable 1 | 217.001 | 29.612 | 62.699 |
| Cable 2 | 154.686 | 979.319 | 139.698 |
| Cable 3 | 49.237  | 105.329 | 40.872 |
| Cable 4 | 34.909  | 36.821  | 59.403 |
| Cable 5 | 137.502 | 105.328 | 96.706 |
| Cable 6 | 61.579  | 36.820  | 57.677 |
| Offset (m) | 8.28   | 7.051   | 6.347 |

The results of the tension and maximum offset for the 4 points mooring configuration in translation motion is presented as Table 8.

Table 8. The results of the tension and maximum offset for the 4 points mooring configuration

| Heading | 0     | 45    | 90     |
|---------|-------|-------|--------|
|         | Tension (N) | Tension (N) | Tension (N) |
| Cable 1 | 14.254 | 32.721 | 1.078.514 |
| Cable 2 | 14.048 | 581.579 | 615.658 |
| Cable 3 | 16.466 | 20.094 | 243.680 |
| Cable 4 | 16.108 | 20.834 | 363.111 |
| Offset (m) | 9.37  | 4.17  | 2.73 |

4.5 The utilization factor
The utilization factor, $U$, is calculated to check whether the mooring line meets with the limit criteria. The utilization factor, $U$, of the mooring system is the comparison between the actual mooring line tension with the mooring line capacity. The results of the utilization factor for the rectangular array mooring configuration is presented as Table 9.
Table 9. The results of the utilization factor for the rectangular array mooring configuration

| Components | U  | Remarks |
|------------|----|---------|
| Cable 1    | 0.15 | pass    |
| Cable 2    | 0.13 | pass    |
| Cable 3    | 0.06 | pass    |
| Cable 4    | 0.06 | pass    |
| Cable 5    | 0.02 | pass    |
| Cable 6    | 0.24 | pass    |
| Cable 7    | 0.08 | pass    |
| Cable 8    | 0.06 | pass    |

The results of the utilization factor for the linear array mooring configuration is presented as Table 10.

Table 10. The results of the utilization factor for the linear array mooring configuration

| Components | U  | Remarks |
|------------|----|---------|
| Cable 1    | 0.18 | pass    |
| Cable 2    | 0.84 | pass    |
| Cable 3    | 0.08 | pass    |
| Cable 4    | 0.04 | pass    |
| Cable 5    | 0.10 | pass    |
| Cable 6    | 0.04 | pass    |

The results of the utilization factor for the 4 points mooring configuration is presented as Table 11.

Table 11. The results of the utilization factor for the 4 points mooring configuration

| Components | U  | Remarks |
|------------|----|---------|
| Cable 1    | 0.945 | pass    |
| Cable 2    | 0.477 | pass    |
| Cable 3    | 0.211 | pass    |
| Cable 4    | 0.316 | pass    |

5. Conclusion

Regarding to the results of the mooring design analysis for the sea station cage that have been performed above, here presents some conclusions as following:

1. The nylon mooring rope type has been selected to be used on the 3 mooring configurations: a) linear array, b) rectangular array, and c) 4 points mooring type. The rope has a diameter of 104 mm with a breaking force of 2.3 MN.
2. The largest tension is occurred on the configuration of the 4 points mooring type which the tension on mooring line is 1078 KN. The mooring configurations of the rectangular array and the linear array type have tensions of 290 KN and 979 KN, respectively.
3. The maximum offset is occurred on the configuration of the 4 points mooring type with offset of 9.3 m, whereas the linear array type has an offset of 8.3 m and the rectangular array type has an offset 6.9 m.
4. Based on results from comparing the 3 mooring configurations, the best mooring configuration is the rectangular array type with the tension on the rope of 290 KN, maximum offset of 6.9 m and the utilization factor of 0.24 based on DNVGL OS-E301.
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