Numerical Study of Environment Loads and Mooring Line Scope Effects to The Buoy Offset

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Abstract. The Indonesian Buoy for Tsunami Early Warning System (INATEWS - Buoy) consists of a tsunami buoy, an ocean bottom unit (OBU), a satellite and a ground station. The changes of the water pressure due to the seismic motion prior to the tsunami event will be acquired by OBU and sent the reading to the tsunami buoy by acoustic signal. One of the conditions that affect the success of sending data from the OBU to the buoy is the distance between the two (offset). Several parameters that are considered to have an effect on the occurrence of offsets on the buoy are the magnitude of the environmental load around the buoy and the value of the scope mooring line used. Environmental loads that consist of current, wave and wind loads are analyzed. Analysis of each environmental load is carried out separately to determine the level of load sensitivity to the offset buoy. In addition, a buoy offset study was also carried out on several scope values from the mooring line to determine the change in the buoy offset. Offset prediction on buoys is calculated by numerical simulation. From this numerical simulation, it found that changes in environmental load, especially changes in current speed, significantly affect the offset value of the buoy that occurs. Likewise with the determination of the mooring line scope, where the smaller the scope value used in the mooring line system, the smaller the offset value that occurs. Finally, the designed mooring systems while applied at the selected operational buoy location, will have Safety Factor 3.61 and 4.57 for wire and nylon rope mooring line components, respectively.

1. Introduction
Geographically, Indonesia is a disaster-prone country, with the potential not only enormous loss of life but also cause damage to public infrastructure and basic connectivity. Based on the tsunami risk map published by BNPB in 2018, more attentions are required to mitigate the risk properly. Hence, an Early Warning System should be produced for minimizing of the tsunami risk [1].

The Agency for the Assessment and Application of Technology (BPPT) as a government institution that focuses on the field of technology, continues to encourage disaster mitigation through the use of technology. The government has now focused on mapping areas that potentially disaster-prone. "Based on historical disaster data in various regions in Indonesia, the relevant ministries and institutions have compiled maps of disaster-prone areas, shown in Figure 1.

The Tsunami Buoy system that developed by BPPT is one of the tsunami early warning systems that works based on anomaly of sea level elevation that passes above the sensor placed on the seabed in the form of the Ocean Bottom Unit (OBU). This system is placed on the open seas, far from the coast. The tsunami buoy system consists of an Ocean Bottom Unit (OBU), and Surface Buoy (SB) platform at sea level that moored to the sea bed. The OBU actively and continuously communicates with the Surface Buoy on the surface via an underwater acoustic modem. The surface buoy acts as a...
data receiver from the OBU and transmits the data via satellite to the tsunami monitoring center at the Read Down Station (RDS). The telemetry system is required for sending tsunami signals to the data processing center at the RDS in real-time/near real time.

In the deployment of a tsunami buoy system on the selected location, there are important things that need to be considered in related to the success of data communication between the buoy and the OBU. These include the response of the buoy motion and the tension that occurs on the mooring line. Among the important buoy motion responses are surge, heave and pitch motions that affect the quality of data communication between the buoy and the OBU. The tension on the mooring line has not to exceed the breaking load limit of the mooring line material so that the mooring system of the buoy system still work properly.

The buoy motion response and mooring line tension are influenced by buoy operational environmental conditions such as wind speed and current as well as wave height and frequency. In addition, the motion response and the mooring line tension are also influenced by the scope value (ratio of mooring line length to operational sea depth) applied during buoy installation.

Figure 1. Location of Earthquake and Tsunami Events and Indonesia Tsunami Risk Map [2]

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The buoy motion response and mooring line tension are influenced by buoy operational environmental conditions such as wind speed and current as well as wave height and frequency. In addition, the motion response and the mooring line tension are also influenced by the scope value (ratio of mooring line length to operational sea depth) applied during buoy installation.
During the buoy operational condition in actual waters, the position of the buoy may experience a significant shift due to unfavorable environmental conditions, such as changes in current speed and sea wave height which were quite large. Under these conditions, the shift of the position of the buoy will reduce the quality of the measurement data signal transmission between the OBU and the buoy. In addition, changes in environmental loads will change the amount of stress that occur at the ends of the mooring line. There is a possibility that the stress that occurs exceeds the breaking load limit of the mooring lines material.

The main purpose of this research is to evaluate numerically the buoy motions response and also strength of the mooring system during buoy’s operational based on the mooring scope value and the environmental loads. The tension intensity should fulfill the minimum safety factor as required by the applied codes or standards, for instance as stated in API RP 2SK [3].

2. Theoretical Basis

Generally, a mooring line of marine structures is arranged of several segments that normally are a combination of chain (heavy cable at the mid-section) and wire rope (lighter cable at the sea surface). This typical combination will increase the stiffness of the mooring system, meanwhile getting a much more lighter cable system [4]. Figure 2 illustrates how a mooring line can be arranged of several segments.

![Figure 2. Example of a Typical Line Segment Composition](image)

Mooring lines have to resist forces that emerge from the vessels static motions, and also the environmental loads that act on the mooring line itself. Current forces will induce drag forces on the line and could give dynamic amplification. This will give various tension forces in the anchor line [4][5]. The next figure shows a mooring line element and the force components that act on the element.

William C. Webster [6] carried out a study showing how mooring lines induce damping for moored skip-like platform roll and surge motions, and the damping of the mooring lines in the fairlead position. Roll motions was studied because the magnitude of roll motions at resonance is governed by damping, and at severe seas surge motions is the most important motion which can lead to quite taut mooring lines. By considering to the energy absorbed by the mooring system, Webster carried out a parameter study that showed the effect of scope (mooring line length and depth ratio), drag coefficient, excitation period, stiffness, and current velocity.

In a research article written by H. Ormberg and K. Larsen [7], they investigate the coupled analysis of a turret-moored ship that illustrated how the current affects the static offset of the mooring lines. Practically, the current has often been neglected when running a mooring line analysis. The mean offset will be invalid by neglecting the current forces completely, while the mean horizontal restoring force will be correct. On the other hand, if the current forces are included as a fixed force on the vessel...
the mean horizontal restoring force will be overestimated, while the static offset will be correct. The inaccuracy will increase with increasing water depth, increasing current velocity, or increasing number of mooring lines. Meanwhile the line tension calculated with or without current is basically unchanged. The unchanged line tension force is due to the fact that current will only change the top end angle of the line, and the tension experience will be the same.

In this paper, a numerical method will be proposed to describe static and dynamic behaviour of the buoy. These static and dynamic behaviour of buoy and also the tension at the end of mooring line was calculated. After the obtained numerical results was presented, these will be analysed and discussed accordingly.

2.1 Irregular wave
The response of floating structures in particular to ships affected by random wave excitation was first introduced by St. Denis and Pierson [8]. The motion of the floating building under ideal conditions can be calculated as a reaction to the excitation of a sinusoidal wave, with a certain characteristic or amplitude and frequency. The calculation is then carried out by taking the wave amplitude which is constant, but the frequency value is varied with certain increment intervals.

A random wave is a superposition of its constituent components in the form of an infinite number of sinusoidal waves. Each wave component has a certain level of energy that is contributed, which is then overall accumulated in the form of a wave energy spectrum, see Figure 3 [9].

![Figure 3. Irregular Waves Record](image)

Figure 3 shows a typical example of wave elevation recordings taken from ocean wave observations. The recording shows a random wave pattern, which cannot be identified by a specific pattern. Thus the wave parameters will be more precisely defined with statistical quantities, as follows:

- $\bar{\zeta}_a$: the average value (mean) of various wave amplitude measurements $\zeta_a$
- $\bar{H}_a$: the average (mean) value of various wave height measurements $H_a$
- $\bar{T}_p$: average value (mean) of various measurements of the peak period of the wave $T_p$
- $\bar{T}_z$: average value (mean) of various measurements of the wave crossover period $T_z$
- $\bar{\zeta}_{1/3}$: the average value of the highest 1/3 total amount of $\zeta_a$, or referred to as the amplitude of the significant wave.
- $\bar{H}_{1/3}$: the average price of the highest 1/3 total number of $H_a$, or referred to as significant wave height.

2.2 Wave Spectra
A measure of the intensity of the components of a sinusoidal wave that forms a random wave, generally expressed in the form of a wave energy amplitude density spectrum (wave energy spectrum). In this case, the amount of energy per one square meter of wave surface, for the $n^{th}$ sinusoidal component of the wave is:
The wave energy spectrum is then defined, so that the area bounded by a certain frequency range (see figure 4) is proportional to the total energy (per m² of sea level) of all wave components in that frequency range. Thus it can be concluded that the total area bounded by the spectrum is proportional to the total energy per m² of the total waveform.

In the design of floating structures, ideally the wave characteristics (spectra) information for the environment in which the structure will be operated must be fully available. However, not all ocean areas in the world will be observed for waves. For design needs, the wave spectra from other locations with similar conditions. If this information is not available, then the wave spectra formulation can be used which can be obtained from various agencies. Currently, a lot of spectra information has been published in the form of an empirical formulation. For the marine world, formulas that are widely known include Pierson Moscowitz [10], Bretschneider [11], Ochi and Hubble [12], JONSWAP [13] and others.

2.3. Mooring Line Analysis

The comprehensiveness evaluation requirement of its mooring system is fundamental for a deep water floating structure. A non-linear analysis of the mooring lines will be performed on the mooring system for floating structure. The floating structure requires some form of a mooring system to hold the vessel within imposed operational positional constraints for the range of sea states and environmental forces to be anticipated during its required life time.

Figure 4. Single Point Mooring Line of Buoy Structure

Figure 4 is basically for a simple mooring system in that only single mooring line is used to restrain the floating structure. In this figure, a uniform cable segment is hanging freely under the water:

- \( l \) = total mooring line length
- \( l_s \) = hanged mooring line length
- \( h \) = water depth
- \( w \) = weight per unit length of chain in water
- \( T_H \) = horizontal mooring force applied at the attached point on the vessel
- \( X \) = horizontal distance of the total mooring line from the attached point to the anchor point
- \( x \) = horizontal distance of the mooring line from the attached point to the touch down point

\[
S_\zeta(\omega) = 0.1687H_1^{2/3} \frac{\omega^2}{\omega^5} e^{-0.675\left(\frac{\omega_s}{\omega}\right)^4}
\]  
(1)
In this case there is only a single line and a horizontal external force greater than the horizontal mooring force $T_H$ would cause the floating body to move laterally until some stable position is reached and $T_H$ is equal to the horizontal external force. The horizontal force is determined in Eq. (2) on the condition that all other values are obtained without the horizontal tension.

The geometry of a catenary mooring line is given.

$$l_s = a \sinh \left( \frac{x}{a} \right)$$  \hspace{1cm} (2)$$

$$h = a \left[ \cosh \left( \frac{x}{a} \right) - 1 \right]$$  \hspace{1cm} (3)$$

where

$$a = \frac{T_H}{w}$$  \hspace{1cm} (4)$$

Combining equations (3) and (4) yields

$$l_s^2 = h^2 + 2ha$$  \hspace{1cm} (5)$$

Substituting equations (5) and (3) for $ls$ and $x$ into the expression $X = l - ls + x$ gets.

$$X = l - h \left( 1 + 2 \frac{a}{h} \right)^{\frac{1}{2}} + a \cosh^{-1} \left( 1 + \frac{h}{a} \right)$$  \hspace{1cm} (6)$$

The maximum tension which occurs at the upper end of the mooring line is given by

$$T_{max} = \left( \frac{wh}{2} \right) \left[ 1 + \left( \frac{l_s}{h} \right)^2 \right] = T_H + wh$$  \hspace{1cm} (7)$$

2.4. Numerical Simulation

A Numerical simulation was performed by using Orcaflex code. For this simulation, a buoy body plan and an environment data is required as a program input. In general, a simulation modelling for calculation is presented as shown in figure 5 below.

As mentioned in the previous chapter that according to the disaster risk map of tsunami, one of the Ina-buoys will be installed in the Indonesian Ocean, which is located at $\pm$ 100 km south of the Cilacap, Central Java.

![Figure 5. Buoy Modelling of Numerical Simulation](image)

In operation, the buoy will be tethered to a sinker which will be dropped to the seabed via a designed mooring system with a configuration system as shown in the following figure:
In correlation to the usage of the mooring system, there are several ratios between the length of the mooring line and the planned sea depth (scope) will be optimised. By doing a numerical simulation, a mooring line configuration will be chosen with a scope value that provides a minimum response to the buoy motion which is considered the most ideal in terms of the transmission range of the measurement data signal.

In order for the purpose of writing this paper to be achieved, it is necessary to plan a numerical simulation data as shown in Table 1, below:

| No. | Selected Variable                        | Value  | Unit | Description                                                                 |
|-----|-----------------------------------------|--------|------|-----------------------------------------------------------------------------|
| 1   | Scope of mooring line                   | 0.81-0.943 | -    | Ratio between total mooring line length and water depth                     |
| 2   | Minimum Breaking Loads                  |        |      |                                                                             |
|     | Mooring Lines Component:                |        |      |                                                                             |
|     | - Wire                                  | 54.192 | kN   | Based on Tensile Test of the material                                      |
|     | - Nylon rope                            | 68.681 | kN   | Based on Tensile Test of the material                                      |
| 3   | Environment conditions:                 |        |      |                                                                             |
|     | - Water depth                           | 3550   | m    |                                                                             |
|     | - Current velocity, Vc                  | 0.5 – 1.2 | m/s | Current velocity at an operational buoy location                            |
|     | - Significant Wave Height, Hs           | 1.25; 2.5; 4 | m | An average of 1/3 heighest wave height                                      |
|     | - Peak Period                           | 10.5   | s    | The wave period associated with the most energetic waves in the total wave spectrum at a specific point |

3. Results and Discussion

3.1 Static Condition

A static calculation was carried out without environmental loads. The calculation was calculated at various scope of mooring line. Based on a numerical calculation has been done, a simulation result has been obtained as shown at Table 2.
Table 2. Numerical Results of Static Condition

| No. | Current Velocity (m/s) | X-Position (Lateral) | Z-Position (Vertical) | End-A Tension (kN) |
|-----|------------------------|----------------------|-----------------------|--------------------|
| 1   | 0,5                    | -295,8466            | -2,2508               | 10,372             |
| 2   | 0,6                    | -414,8808            | -2,2603               | 10,622             |
| 3   | 0,7                    | -544,0096            | -2,2741               | 10,985             |
| 4   | 0,8                    | -677,9770            | -2,2922               | 11,463             |
| 5   | 0,9                    | -812,8045            | -2,3141               | 12,045             |
| 6   | 1,0                    | -945,0158            | -2,3394               | 12,719             |

Figure 7. Z-Position (Draft) of Buoy at Various Scope Mooring Line

3.2. Dynamic Condition

A dynamic calculation was carried out with environmental loads. The calculation was calculated at various scope of mooring line and a variation of current velocity and a variation of wave spectra. Based on a numerical calculation under current load effect only has been done, a simulation result has been obtained as shown at Table 3.
Table 3. Numerical Results of Dynamic Condition as Function Current Velocity at Various Scope of Mooring Line

| Scope | No. | Current Velocity (m/s) | X-Position (Lateral) | Z-Position (Vertical) | End-A Tension (kN) |
|-------|-----|------------------------|----------------------|-----------------------|---------------------|
| 0.887 | 1   | 0.5                    | -295.8466            | -2.2508               | 10.372              |
|       | 2   | 0.6                    | -414.8808            | -2.2603               | 10.622              |
|       | 3   | 0.7                    | -544.0096            | -2.2741               | 10.985              |
|       | 4   | 0.8                    | -677.9770            | -2.2922               | 11.463              |
|       | 5   | 0.9                    | -812.8045            | -2.3141               | 12.045              |
|       | 6   | 1.0                    | -945.0158            | -2.3394               | 12.719              |

| Scope | No. | Current Velocity (m/s) | X-Position (Lateral) | Z-Position (Vertical) | End-A Tension (kN) |
|-------|-----|------------------------|----------------------|-----------------------|---------------------|
| 0.901 | 1   | 0.5                    | -339.1303            | -2.2064               | 9.327               |
|       | 2   | 0.6                    | -470.4843            | -2.2181               | 9.544               |
|       | 3   | 0.7                    | -609.2292            | -2.2345               | 9.975               |
|       | 4   | 0.8                    | -749.7135            | -2.2551               | 10.519              |
|       | 5   | 0.9                    | -888.4377            | -2.2794               | 11.163              |
|       | 6   | 1.0                    | -1023.6699           | -2.3067               | 11.889              |

| Scope | No. | Current Velocity (m/s) | X-Position (Lateral) | Z-Position (Vertical) | End-A Tension (kN) |
|-------|-----|------------------------|----------------------|-----------------------|---------------------|
| 0.915 | 1   | 0.5                    | -392.7513            | -2.1648               | 8.176               |
|       | 2   | 0.6                    | -536.4901            | -2.1793               | 8.554               |
|       | 3   | 0.7                    | -683.4942            | -2.1985               | 9.059               |
|       | 4   | 0.8                    | -828.6119            | -2.2218               | 9.671               |
|       | 5   | 0.9                    | -969.4494            | -2.2483               | 10.372              |
|       | 6   | 1.0                    | -1105.2645           | -2.2773               | 11.143              |
### Scope 0,929

| No. | Current Velocity (m/s) | X-Position (Lateral) (m) | Z-Position (Vertical) (m) | End-A Tension (kN) |
|-----|------------------------|--------------------------|--------------------------|-------------------|
| 1   | 0,5                    | -459,4623                | -2,1264                  | 7,193             |
| 2   | 0,6                    | -614,1504                | -2,1440                  | 7,654             |
| 3   | 0,7                    | -766,8609                | -2,1662                  | 8,234             |
| 4   | 0,8                    | -914,1496                | -2,1918                  | 8,910             |
| 5   | 0,9                    | -1055,1610               | -2,2202                  | 9,660             |
| 6   | 1,0                    | -1190,1778               | -2,2507                  | 10,47             |

### Scope 0,943

| No. | Current Velocity (m/s) | X-Position (Lateral) (m) | Z-Position (Vertical) (m) | End-A Tension (kN) |
|-----|------------------------|--------------------------|--------------------------|-------------------|
| 1   | 0,5                    | -541,6797                | -2,0919                  | 6,314             |
| 2   | 0,6                    | -703,6908                | -2,1130                  | 6,862             |
| 3   | 0,7                    | -858,5660                | -2,1378                  | 7,513             |
| 4   | 0,8                    | -1055,2561               | -2,1655                  | 8,242             |
| 5   | 0,9                    | -1144,6047               | -2,1954                  | 9,031             |
| 6   | 1,0                    | -1277,6268               | -2,2269                  | 9,870             |

**Figure 8.** Buoy Position as Function Current Velocity at Various Scope of Mooring Line
Based on the numerical calculation under current and wave effect has been done, a simulation result has been obtained as shown at Table 4.

**Table 4. Numerical Results of Dynamic Condition on Certain Current Velocity and a Various Waves Spectra**

| Scope | Wave Height, Hs (m) | X-Position (Lateral) | Z-Position (Vertical) | End-A Tension (kN) |
|-------|---------------------|----------------------|-----------------------|-------------------|
| No.   |                     |                      |                       |                   |
| 1     | 0.5                 | -1082.588            | -1.884                | 13.382            |
| 2     | 1.25                | -1084.992            | -1.945                | 13.264            |
| 3     | 2.5                 | -1092.556            | -2.130                | 13.464            |
| 4     | 4.0                 | -1109.552            | -3.069                | 15.028            |
| 5     | 6.0                 | -1153.380            | -4.095                | 14.956            |

Based on the numerical simulation results obtained as shown in Table 3 and Figure 8, it can be seen that the greater current velocity, the greater the position of the buoy in the lateral direction (x-axis direction), in other words, the buoy position will be further away from the initial position of the buoy. In addition, the greater current velocity, the greater buoy's position in the vertical direction (z-axis direction). This means that the draft of the buoy will increase.

From Figure 8, it can be seen that there is a tendency that the greater the scope value of the mooring line that applied to the buoy mooring system, the greater offset of the buoy and buoy draft.

In the offset analysis of the buoy position and tension that occurs on the mooring line, table 4 shows a tendency that the effect of waves into buoy position and tension line at the ends of the mooring line is insignificant when compared to the effect of current velocity. Finally, the designed mooring systems while applied at the selected operational buoy location, will have a Safety Factor 3.61 and 4.57 for wire and nylon rope mooring line components, respectively.

### 4. Conclusion
In design of the Ina Buoy to support the Tsunami early warning system, a numerical simulation of the effects of the environment loads and scope of mooring line has been conducted.

Based on the analysis of the numerical results, the following conclusions can be drawn:

- The greater current velocity, the buoy position (lateral direction) will be further away from the initial position of the buoy.
- The greater current velocity, the draft (T) of the buoy will also be increased.
- There is a tendency that the greater the scope value of the mooring line that applied to the buoy mooring system, the greater offset of the buoy and buoy draft will be experienced.
- The effect of waves into buoy position and tension line at the ends of the mooring line is insignificant when compared to the effect of current velocity.
- The Safety Factor of the designed mooring system are comply with the API RP2SK Standard Code.

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