Risk Assessment of Subsea Pipeline due to Installation and Operation of Single Point Mooring (SPM)

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Abstract. Offshore exploration facilities located in remote areas require high investment and high operational cost, the assets are classified as vital assets for the companies. The careful study and examination is therefore required to ensure that the risk of the facility is acceptable. Offshore exploration used subsea pipelines that has several risks if the accident occurs. Based on historical data, most of subsea pipelines failures are caused by third party factors (dropped anchor, dragged anchor, and ship sinking). This paper examines risk assessment of subsea pipelines due to installation and operation of SPM is assessed used DNVGL RP F107 standard and numerical simulations. Frequency is assessed by using Bayesian Network methods. Whereas the consequences were assessed by using calculations on the DNVGL RP F107 standard and FEM simulation. The results of frequency and consequences are mapped within a risk matrix according to DNVGL RP F107. The risk matrix shows that the risk level are in acceptable and ALARP condition. Acceptable obtained by frequency in rank 1 and the consequence in rank 3 and 4. While ALARP obtained by frequency rank 1 and consequence rank 5. Although it is not mandatory for mitigation, it is recommended to provide the subsea pipeline with external protection. Rock dumping is recommended as external protection for subsea pipelines due to the good ability to protect the subsea pipelines and it has lower cost compared to concrete mattress.

1. Introduction

Energy is a primary need in social and economic development of every country [1]. The Indonesian government still relies on oil and gas as the main energy source [2], where is the oil and gas industry in contributing 42% of Non-Tax State Revenue in 2018 [3]. Exploration of oil and gas resources is therefore to be continuously carried out to meet the energy demands. At present, the upstream oil and gas industry in Indonesia has begun to shift from old onshore wells to offshore exploration where 70% of the potential oil and gas reserves are in those areas [4]. Offshore exploration located in remote areas requires high investment and operations cost, the assets are classified as vital assets for the companies [5].

Offshore exploration is inseparable from the use of subsea pipeline as transportation to deliver products. In addition, subsea pipeline should have an integrity that able to operate safely and be able to withstand the workload during its lifecycle [6]. However, the subsea pipeline has several risks that can endanger the environment if the accident occurs [7]. In addition, the company will also bear financial losses due to cessation of production, cleaning up the oil and gas spills, victims'
compensation costs, and repair of facilities [8, 9]. Subsea pipelines have been a special concern since the 80s when there were accidents on subsea pipelines although the impact of these events has not been deeply evaluated [10]. Historical and literature review of subsea pipeline failures and incidents shows that the accident can be caused by several factors such as third parties damage, corrosion, and operational errors [11, 12]. The third parties damage became the biggest contributor to the failure of the subsea pipeline, which was 38%, then followed by corrosion by 36%.

Common factors of third party damage that can affect the subsea pipeline include: fishing activities, commercial anchoring activities (i.e. emergency anchoring, dragged anchors, dropped containers, and ship sinking), and construction vessel activities [8]. If an accident occurs in the pipeline under the last in the production area, it will cause damage to the pipe and cause impacts such as deflection and rupture. Approximately 11 incidents caused by ship anchors were recorded by the Health and Safety Executive (HSE) and Pipeline and Riser Loss of Containment (PARLOC) on 25,000 km of subsea pipelines in 1991-2001 [13]. The careful study and examination is therefore required to ensure that the risk of the facility is acceptable [14].

One of oil and gas company utilizes a subsea pipeline to distribute oil and gas. Gas products are channelled to onshore facilities using subsea pipelines, while oil products are channelled from platforms to onshore facilities using Floating Storage and Offloading units (FSO). Due to subsea pipeline maintenance that used to distribute oil from the platform to the FSO, a temporary Single Point Mooring (SPM) will be installed to accommodate crude oil production from a platform. This paper examines risk assessment of subsea pipelines due to the installation and operation of Single Point Mooring (SPM) based on DNVGL RP F107 standard. Frequency is assessed by using Bayesian Network methods. Whereas the consequences were assessed by using calculations on the DNVGL RP F107 standard and Finite Element Method (FEM).

2. Methods

Risk is a parameter to determine the safety level of a system in which risk has two important parameters namely frequency and consequences. If the frequency and consequences of a hazard are high, it can be concluded that the hazard has a high-risk level [11]. In offshore exploration using subsea pipelines proven to be safe and reliable in distributing oil and gas. However, some risk factors might cause subsea pipeline failure, where external factors are the highest contributor in the subsea pipeline failure [12].

Risk assessment applied as a methodology on this paper which consisted of several processes:

- Hazard Identification
- Frequency Assessment
- Consequence Assessment
- Risk Assessment and Mitigation

2.1. Hazard Identification

Hazard identification carried to find out what are the possible hazards that can cause failure to the subsea pipeline during installation and operation period of Single Point Mooring (SPM). Possible hazards that can cause failures to the subsea pipeline are identified based on activities in the area [15]. By considering the location of installation and operation, the SPM will be installed near the platform with a depth of sea about 54 meters and it is above the subsea pipeline that can be seen in Figure 1. The hazard identification for subsea pipeline is divided into two conditions:

1. SPM Installation: Some AHTS are operated during SPM installation. In addition, one tanker is moored to SPM as a temporary oil storage facility.

2. SPM operations: Some tugboats and shuttle tankers are operated during the operational process of SPM. In addition, the activity of ship traffic around the SPM is considered because it is feared that it will affect the subsea pipeline.

The number of ship traffic based on Automatic Identification System (AIS) data near the single point mooring (SPM) installation area can be seen in Table 1.
Figure 1. Single Point Mooring Layout

Table 1. Number of Ship Traffic

| Type of Vessel | Number of Vessel |
|----------------|------------------|
| Passenger      | 5432             |
| Cargo          | 11703            |
| Tanker         | 7677             |
| Container      | 9854             |
| Tug            | 1262             |

2.2. Frequency Assessment

Frequency is a potentially unwanted event that is expressed as an event per unit of time, usually expressed per year. Frequencies can be obtained through historical data, frequency modelling, expert judgement, and others. Some methods of modelling the frequency of hazards are Fault Tree Analysis (FTA), Event Tree Analysis (ETA), Markov Chain, Bayesian Network, and others. FTA and ETA are conventional methods that are effectively proven for frequency modelling of failure in a piping system. ETA and FTA analysis are limited to modelling simple static systems compared to other modelling methods that can capture the variation of risk [16].

Event Tree Analysis (ETA) is commonly used to determine the frequency in subsea pipeline frequency assessment. Event Tree Analysis (ETA) method used by Artana (2009) to calculate the hazards frequency of anchor drop by using joint probability concept where the probability of dropped anchor hit the pipeline is a combination of the probability of ship in Critical Anchor Damage Zone (CADZ), combined with the probability of the ship dropped anchor and the probability of which group the anchor dropped [7]. ETA method is also used to calculate the frequency of threatening hazards during the hot-tapping installation process [17] and used to calculating the probability of a dragged anchor [18].

Mulyadi (2013), used the Bayesian Network method used to identify and calculate the frequency of dragging anchor hazards in subsea pipelines [13] and also used for frequency modelling in ship sinking [19]. The Bayesian Network method was also applied by Sulaiman and Tan, (2014) for frequency modelling of dropped anchor and also calculate the impact of the subsea pipeline due to dropped anchor [12]. Bayesian Network method can be used widely in the subsea pipeline risk assessment because the Bayesian Network has a more flexible structure compared to Event Tree Analysis or Fault Tree Analysis [20]. This paper uses Bayesian Network methods to model the frequency assessment. The result of frequency assessment is classified into the DNVGL RP F107 as shown in Table 2.
2.3. Consequence Assessment

The consequences are the effects when the accident occurred which is stated as an effect per event. The consequences can be assessed in several aspects, such as social, financial, environmental, and others. This paper will be comparing the calculation method and the Finite Element Method (FEM) for consequence assessment. The external factors impact to the subsea pipeline is mostly denting and in certain condition can cause rupture [15]. The result of consequence assessment is classified into the DNVGL RP F107 as shown in Table 3. Dent prediction model according to DNVGL RP F107 standard can be seen in Figure 2, dent absorbed energy is given in equation 1, and impact resistance of concrete coating is given in equation 2.

### Table 2. Annual Failure Frequency Ranking

| Category | Description | Annual Frequency |
|----------|-------------|------------------|
| 1 (Low)  | Likelihood of event considered negligible. | <10<sup>-5</sup> |
| 2        | Event rarely expected to occur. | 10<sup>-5</sup>−10<sup>-4</sup> |
| 3 (Medium) | Unlikely for a single pipeline, but may happen once a year given a large number of pipelines. | 10<sup>-3</sup>−10<sup>-2</sup> |
| 4        | Event individually may be expected to occur during the lifetime of the pipeline. (Typically a 100 year storm) | 10<sup>-2</sup>−10<sup>-3</sup> |
| 5 (High) | Event individually may be expected to occur more than once during lifetime. | >10<sup>-2</sup> |

### Table 3. Consequence Ranking

| Dent/Diameter (%) | Damage Description |
|-------------------|--------------------|
| <5                | Minor damage       |
| 5-10              | Major damage, Leakage anticipated |
| 10-15             | Major damage, Leakage, and rupture anticipated |
| 15-20             | Major damage, Leakage, and rupture anticipated |
| >20               | Rupture            |

\[
E = 16 \cdot \left( \frac{2\pi}{a} \right) \times m_p \cdot \left( \frac{D}{R} \right)^2 \cdot D \cdot \left( \frac{\delta}{n} \right)^2 \quad (1)
\]

Where:
- \( m_p \): plastic moment capacity of the wall \( \left( = \frac{1}{a} \times \sigma_y \times T^2 \right) \)
- \( D \): steel outer diameter.
- \( T \): wall thickness (nominal)
- \( \delta \): pipe deformation, dent depth
- \( \sigma_y \): yield stress

\[
E_c = Y \times b \times h \times x_0 \quad (2)
\]

Where:
- \( Y \): Crushing Strength
- \( b \times h \): Area of Impacting Object
- \( x_0 \): Concrete Coating Thickness

The traffic of vessel can cause several accident such as dropped anchor, dragged anchor, and ship sinking. The impact of damage can be calculate by comparing the kinetic energy of dropped object
and the energy needed to make a dent the subsea pipeline [21]. The impact energy of dropped anchor is given in equation 3.

$$E = \frac{1}{2} \rho_{water} \cdot g \cdot \left( m - V \cdot \rho_{water} \right) \cdot \sqrt{\frac{2}{\rho_{water}}}$$

Where:
- \( m \): Mass of the object (kg)
- \( g \): Gravitation acceleration (9.81 m/s²)
- \( V \): Volume of the object (m³)
- \( \rho_{water} \): Density of water (1025 kg/m³)
- \( C_D \): Drag-coefficient of the object
- \( A \): Projected area of the object in the flow-direction (m²)
- \( v_T \): Terminal velocity through the water (m/s).

The effective impact energy of dropped anchor is given in equation 4.

$$E_{\text{eff}} = E_T + E_A = \frac{1}{2} \left( m + m_a \right) \times v_t^2$$

Where:
- \( m \): Mass of the object (kg)
- \( m_a \): Added mass (kg)
- \( v_t \): terminal velocity (m/s)
- \( C_a \): Added mass coefficient

Based on DNVGL RP F107, drag and added mass coefficient shown in Table 4. The initial value of 1.0 is recommended for drag coefficient that used for consequence calculation according to DNVGL RP F107 standard.

Table 4. Drag and Added Mass Coefficient

| Category | Description               | \( C_D \) | \( C_a \) |
|----------|---------------------------|----------|----------|
| 1,2,3,5  | Slender Shape             | 0.7 – 1.5| 0.1 – 1.0|
| 4,5,6,7  | Box Shaped                | 1.2 – 1.3| 0.6 – 1.5|
| All      | Misc. Shaped (spherical to complex) | 0.6 – 2.0| 1.0 – 2.0|

Consequence analysis of dragged anchor is done by using Autopipe software simulation. The drag force of the anchor depends on the thrust generated by the ship where the drag anchor will deliver kinetic energy to the subsea pipeline [22]. The simulation on Autopipe software is done by applying force to the subsea pipeline according to the maximum breaking load of the ship's anchor chain.

Ship sinking is one of the hazard that also be calculate into consideration the underwater pipeline is an important asset. Damage to the subsea pipeline due to the sinking ship is a complex system and involves a number of specific variables related to the hull, subsea pipeline and interactions on the seabed [17,23]. Therefore, for consequence analysis of ship sinking, the model is simplified, where the ship is considered to be sinking slowly in a horizontal position as shown in Figure 3. Another assumption is that the density of the ship's steel plate is 7850 kg/m³. Ship deadweight tonnage (DWT) is used in the calculation and estimation of the weight immersed in water.

Figure 3. Ship Sinking Modelling

2.4. Risk Assessment and Mitigation

DNVGL RP F107 was adopted as a standard for risk assessment of this paper. Risk assessment is done by classified the frequency and conseuency into the risk matrix. Figure 4 is the risk matrix according
to DNVGL RP F107 standard. The risk matrix consists of 5x5 matrix to determine risk level according to the frequency and consequence ranking [15].

Risk mitigation is carried out to minimize the risk of hazard if risk level is not acceptable. Cost-Benefit Analysis method used to select the best method to minimize the risk due to the hazard. The costs and benefits of a mitigation method are calculated and compared so as to get the right mitigation steps with low costs and high benefits. Installation of concrete mattress and rock dumping are possible method to mitigate the risk due to hazard to subsea pipeline.

![Figure 4. Risk Matrix](image)

3. Results

3.1. Hazard Identification
Based on activity and traffic analysis on the area of SPM installation and operation, the possible hazard that can cause failures to the subsea pipeline are dropped anchor, dragged anchor, and ship sinking. From the possible hazard to subsea pipeline is then breaks down into hazard compatibility matrix as shown on Table 5.

| Type of Vessel       | Dropped Anchor | Dragged Anchor | Ship Sinking |
|----------------------|----------------|----------------|--------------|
| AHTS                 | v              | v              | -            |
| Storage Tanker       | v              | v              | -            |

3.2. Frequency Assessment
The hazard frequency is calculated to classify the frequency level. This paper evaluated the frequency level by using Bayesian Network. Based on the identification of hazards, the following are possible hazards that can affect the subsea pipeline during installation and operation of SPM:

1. Dropped Anchor: Frequency assessment on dropped anchors is based on the probability of the ship dropped anchor on the Critical Anchor Damage Zone (CADZ), the vessel in CADZ, the annual frequency of the ship passing CADZ, and in a state of loss of control that is influenced by several factors: weather, human performance, engine failure, or steering system failure. The
frequency assessment of dropped anchors is carried out at the SPM Installation and Operation condition. Bayesian Network of dropped anchors can be seen in Figure 5.

![Figure 5. Bayesian Network of Dropped Anchor](image)

Figure 5. Bayesian Network of Dropped Anchor

2. Dragged Anchor: Frequency assessment on dragged anchors is based on the probability of the ship dropped anchor on the Critical Anchor Dragged Zone (CADRZ), the vessel in CADRZ, the annual frequency of the ship passing CADRZ, and in a state of loss of control that is influenced by several factors: weather, human performance, engine failure, or steering system failure. The frequency assessment of dragged anchors is carried out at the SPM Installation and Operation condition. Bayesian Network of dropped anchors can be seen in Figure 6.

![Figure 6. Bayesian Network of Dragged Anchor](image)

Figure 6. Bayesian Network of Dragged Anchor

3. Ship Sinking: Frequency assessment on ship sinking is based on the probability of the annual frequency of the ship passing Critical Sinking Zone (CSZ), vessel in cross area, collision in cross area, hull damage due to collision, and in a state of loss of control that is influenced by several factors: weather, human performance, engine failure, or steering system failure. The frequency assessment of ship sinking is carried out at the SPM Installation and Operation condition. Bayesian Network of dropped anchors can be seen in Figure 7.

![Figure 7. Bayesian Network of Ship Sinking](image)

Figure 7. Bayesian Network of Ship Sinking

The result of frequency assessment is then classified into the frequency ranking according to DNVGL RP F107 standard as seen on Table 6.
Table 6. Summary of Frequency Assessment

| Threat Description | Installation of SPM | Operation of SPM |
|--------------------|---------------------|------------------|
|                     | Vessel Speed (knot) | Vessel Speed (knot) |
|                     | 0.25 | 0.5 | 0.75 | 0.25 | 0.5 | 0.75 |
| Dropped Anchor      |       |     |      |       |     |      |
| Passenger           | N/A   | N/A | N/A  | 1     | 1   | 1    |
| Cargo               | N/A   | N/A | N/A  | 1     | 1   | 1    |
| Tanker              | 1     | 1   | 1    | 1     | 1   | 1    |
| Container           | N/A   | N/A | N/A  | 1     | 1   | 1    |
| Tug                 | 1     | 1   | 1    | 1     | 1   | 1    |
| Dragged Anchor      |       |     |      |       |     |      |
| Passenger           | N/A   | N/A | N/A  | 1     | 1   | 1    |
| Cargo               | N/A   | N/A | N/A  | 1     | 1   | 1    |
| Tanker              | 1     | 1   | 1    | 1     | 1   | 1    |
| Container           | N/A   | N/A | N/A  | 1     | 1   | 1    |
| Tug                 | 1     | 1   | 1    | 1     | 1   | 1    |
| Ship Sinking        |       |     |      |       |     |      |
| Passenger           | N/A   | N/A | N/A  | 1     | 1   | 1    |
| Cargo               | N/A   | N/A | N/A  | 1     | 1   | 1    |
| Tanker              | N/A   | N/A | N/A  | 1     | 1   | 1    |
| Container           | N/A   | N/A | N/A  | 1     | 1   | 1    |
| Tug                 | N/A   | N/A | N/A  | 1     | 1   | 1    |

3.3. Consequency Assessment

The hazard based on the hazard identification to subsea pipeline due to installation and operation of Single Point Mooring (SPM) are dropped anchor, dragged anchor, and ship sinking. This paper considers the material properties of API5L X52. Table 7 shown the material properties and simulation consideration used in this paper. While table 8 shown the range of dent per diameter according to the impact energy calculation on DNVGL RP F107 Standard.

Table 7. Subsea Pipeline Properties

| Property          | Value | Unit |
|-------------------|-------|------|
| Material Grade    | API 5L|      |
| Outer Diameter    | 406.4 | mm   |
| Wall Thickness    | 12.7  | mm   |
| Density           | 7850  | Kg/m³|
| Young’s Modulus   | 2.1E+11| Pa   |
| Poisson’s Ratio   | 0.30  | Pa   |
| Sea Surface Heigh | 54    | m    |
| Sea Water Density | 1025  | Kg/m³|

Table 8. Range of Impact Energy

| Dent/Diameter (%) | Impact Energy Steel Pipe Only |
|-------------------|-------------------------------|
| <5                | < 5.47                        |
| 5-10              | 5.47 - 15.48                  |
| 10-15             | 15.48 - 28.44                 |
| 15-20             | 28.44 - 43.79                 |
| >20               | > 43.79                       |

3.3.1. Dropped Anchor

The consequency ranking obtained by classified the total energy absorbed by the subsea pipeline. Referring to DNVGL RP F107, the total energy includes energy that can be absorbed by the subsea pipeline and the energy that can be absorbed by pipe protection systems such as Concrete Coating, Polymer Coating, Gravel Dump, and other protection systems [15]. Table 9 is the summary of impact energy calculation and ranking consequency ranking of each type of ship for ship sinking.
Table 9. Summary of Dropped Anchor

| Type of Vessel | Concrete Absorbed Energy (kJ) | Impact Energy (kJ) | Dent (mm) | Percentage | Rank |
|---------------|-------------------------------|-------------------|-----------|------------|------|
| Passenger     | 14.95                         | 46.157            | 64.61     | 15.90%     | 4    |
| Cargo         | 16.258                        | 119.036           | 159.35    | 39.21%     | 5    |
| Tanker        | 17.884                        | 171.500           | 226.64    | 55.77%     | 5    |
| Container     | 16.258                        | 107.450           | 144.02    | 35.44%     | 5    |
| Tug           | 12.334                        | 32.549            | 50.07     | 12.32%     | 3    |

In addition to using calculations based on DNVGL RP F107 standards, this paper also evaluates the impact of the dropped anchor by using Finite Element Method (FEM). Anchor and subsea pipeline modelled in 3 dimensions to be simulated by using FEM software as shown in Figure 8. The simulation considered the material and environmental condition as shown in Table 10. FEM simulation is able to visualize the impact of the dropped anchor to the subsea pipeline as shown in Figure 9.
Table 10. Summary of the simulation results with FEM software shown in Table

| Type of Vessel | Total Impact (kJ) | FEM Dent (mm) | Dent/Diameter | Rank |
|---------------|------------------|---------------|---------------|------|
| Passenger     | 45.853           | 58.036        | 14.28%        | 3    |
| Cargo         | 107.31           | 141.71        | 34.87%        | 5    |
| Tanker        | 161.54           | 210.88        | 47.56%        | 5    |
| Container     | 96.559           | 122.52        | 30.15%        | 5    |
| Tug           | 33.221           | 44.33         | 10.91%        | 3    |

Figure 11 is a comparison of the results of the impact energy due to dropped anchor between DNVGL RP F107 and FEM. Based on the graph, there are differences in the results between calculations and FEM simulations. The smallest difference in the impact energy value is in the Passenger vessel, where the calculation result is 46.16 kJ and the simulation result is 45.853 kJ so the difference between the calculation and FEM simulation is 0.303 kJ. While the largest difference in value on a cargo vessel, where the impact energy value on the calculation is 119.04 kJ and FEM simulation results are 107.31 kJ with the difference between the two is 11.72 kJ.

![Calculation Vs FEM (Impact Energy)](image)

Figure 10. Impact Energy Comparison

The dent comparison of the results of DNVGL RP F107 standard calculations and FEM simulation can be seen in Figure 12. Based on these graphs, it can be seen that there is a dent value difference that occurs in the subsea pipeline. The smallest dent value difference in the Tug vessel, which based on the calculation results has a dent value of 50.07 mm and the FEM simulation result is 44.33 mm so that it has a value difference of 5.74 mm. While the largest difference in value occurs in ships with the type of Container, where the dent value in the calculation is 144.01 mm and the results of FEM simulation are 122.52 mm so that it has a value difference of 21.49 mm. The difference between the DNVGL RP F107 standard calculation and FEM simulation is likely to occur due to the different of approaches on the two methods, where the DNVGL RP F107 standard is based on modelling on the knife hit the object while FEM simulation is done by dividing the shape of the object into a net mesh for numerical calculations.
3.3.2. Dragged Anchor

Consequences Analysis of dragged anchor is done by stress analysis and displacement using Autopipe software. Stress and displacement analysis is done by entering the value of external force produced by each ship. This external force is taken from the breaking load of the anchor chain as shown in Table 11.

| Type of Vessel | Anchor Chain Diameter (mm) | Breaking Load (kN) |
|----------------|---------------------------|-------------------|
| Passenger      | 42                        | 703               |
| Cargo          | 62                        | 1470              |
| Tanker         | 58                        | 1290              |
| Container      | 56                        | 1220              |
| Tug            | 40                        | 640               |

Figure 12 and Figure 13 are examples of stress and displacements analysis using Autopipe software for passenger-type vessels. From the stress analysis can be seen that the allowable stress on the pipe is 151.68 N / mm², however, the stress value generated as a result of a given external force is 365 N / mm² where the value exceeds the value of the allowable stress and cause displacement of 92.94 mm. All references should be numbered in square brackets in the text and listed in the References section in the order they appear in the text.
Summary of stress and displacements analysis, and the consequence ranking for dragged anchor according to DNVGL RP F107 shown in Table 12.

Table 12. Summary of Dragged Anchor Simulation

| Type of Vessel | Stress (N/mm²) | Allowable (N/mm²) | Total Displacements (mm) | Displacement/Diameter (%) | Rank |
|----------------|----------------|------------------|--------------------------|---------------------------|------|
| Passenger      | 572.08         | 151.68           | 139.31                   | 34%                       | 5    |
| Cargo          | 1085.94        | 151.68           | 291.3                    | 72%                       | 5    |
| Tanker         | 957.79         | 151.68           | 255.63                   | 63%                       | 5    |
| Container      | 903.79         | 151.68           | 241.76                   | 60%                       | 5    |
| Tug            | 481.18         | 151.68           | 126.83                   | 31%                       | 5    |

3.3.3. Ship Sinking

Kinetic energy of ship sinking is calculated to do a consequence analysis. From these calculations, the result will be classified into DNVGL RP F107 Standard. Table 13 is the summary of impact energy calculation and ranking consequence ranking of each type of ship for ship sinking. Based on Table 10, the consequence ranking ship sinking is on 5 for all types of vessels. It is means that there will be rupture of the pipeline when the ship sinking hit the subsea pipeline.

Table 13. Summary of Ship Sinking

| Type of Vessel | Absorbed Energy (kJ) | Impact Energy (kJ) | Dent/Diameter (%) | Rank |
|----------------|----------------------|--------------------|-------------------|------|
| Passenger      | 1,083.87             | 7,308.93           | > 20%             | 5    |
| Cargo          | 1,083.87             | 222,253.92         | > 20%             | 5    |
| Tanker         | 1,083.87             | 810,240.47         | > 20%             | 5    |
| Container      | 1,083.87             | 241,586.42         | > 20%             | 5    |
| Tug            | 1,083.87             | 19,184.43          | > 20%             | 5    |

3.4. Risk Assessment and Mitigation

The results of frequency and consequence assessment is then mapped within a 5x5 risk matrix according to DNVGL RP F107. Table 14 shown the summary of risk level of hazards during installation and operation of Single Point Mooring (SPM). According to risk level on Table 14, risk level in acceptable and ALARP regions. These regions mean that the risk still acceptable and no further mitigation requires. Although it is not mandatory for mitigation, it is recommended to provide the subsea pipeline with external protection. Concrete mattress or rock dumping was proposed as external protection on this paper. Concrete mattress or rock dumping as shown on Figure 14 and Figure 15 was proposed as external protection on this paper. According to FEM simulation, either concrete mattress or rock dumping was able to protect the subsea pipeline. Based on cost analysis to install external protection for 2514 meter of subsea pipeline, Concrete mattress need Rp.
3,212,851,249.15 for material and installation cost of Rp. 4,991,622,921.83. While rock dumping need Rp. 976,671,169.00 for material and installation cost of Rp 3,876,510,294.00.

### Table 14. Summary of Risk Level

| Threat Description | Installation of SPM | Operation of SPM |
|--------------------|---------------------|------------------|
|                    | Vessel Speed (knot) | Vessel Speed (knot) |
| 0.25               | 0.5                 | 0.75             | 0.25 | 0.5 | 0.75 |
| Dropped Anchor     |                     |                  |
| Passenger          | N/A                 | N/A              | (1.4) | (1.4) | (1.4) |
| Cargo              | N/A                 | N/A              | (1.5) | (1.5) | (1.5) |
| Tanker             | (1.5)               | (1.5)            | (1.5) | (1.5) | (1.5) |
| Container          | N/A                 | N/A              | (1.5) | (1.5) | (1.5) |
| Tug                | (1.3)               | (1.3)            | (1.3) | (1.3) | (1.3) |
| Dragged Anchor     |                     |                  |
| Passenger          | N/A                 | N/A              | (1.5) | (1.5) | (1.5) |
| Cargo              | N/A                 | N/A              | (1.5) | (1.5) | (1.5) |
| Tanker             | (1.5)               | (1.5)            | (1.5) | (1.5) | (1.5) |
| Container          | N/A                 | N/A              | (1.5) | (1.5) | (1.5) |
| Tug                | (1.5)               | (1.5)            | (1.5) | (1.5) | (1.5) |
| Ship Sinking       |                     |                  |
| Passenger          | N/A                 | N/A              | (1.5) | (1.5) | (1.5) |
| Cargo              | N/A                 | N/A              | (1.5) | (1.5) | (1.5) |
| Tanker             | N/A                 | N/A              | (1.5) | (1.5) | (1.5) |
| Container          | N/A                 | N/A              | (1.5) | (1.5) | (1.5) |
| Tug                | N/A                 | N/A              | (1.5) | (1.5) | (1.5) |

4. Conclusions

During the Single Point Mooring (SPM) installation, there are such potential hazard to the subsea pipeline such as dropped anchors and dragged anchors. Whereas, during the SPM operation there are potential risks such as dropped anchors, dragged anchors, and ship sinking.

The risk to subsea pipeline due to dropped anchor during SPM installation for Tug vessel is acceptable and tankers is on ALARP condition. The risk to subsea pipeline due to dropped anchor at the SPM operation for Tug and Passenger is acceptable, while the cargo, tankers, and containers are in ALARP condition. The risk to subsea pipeline due to dragged anchor and ship sinking for all types of ship are in ALARP condition.

Based on the Finite Element Method (FEM) simulation, the concrete coating has cracked due to dropped anchors on all types of vessels. While subsea pipeline dent due to dropped anchor of passenger ships, tugs, cargo, tankers, and containers are 58,036 mm, 44.33 mm, 141.71 mm, 193.27 mm, 122.52 mm.

There is an ALARP category on the hazard due dropped anchors, dragged anchors and ship sinking where the risk mitigation is not mandatory on acceptable and ALARP condition. Although it is
not mandatory for mitigation, it is still recommended to equip the underwater pipeline with external protection such as rock dumping and concrete mattress. In terms of costs and benefits rock dumping is proposed as external protection for subsea pipeline because it has a good ability to protect the subsea pipeline from collisions and has a lower material and installation cost compared to concrete mattresses, which is Rp. 3,876,510,294 for 2,514 meter of subsea pipeline.

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