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# Submarine Operational Risk Management Design in Support of the Indonesian Navy's Tasks

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**Abstract**

This research discusses risk management faced by submarines and their crews. One of the risks that can occur is that the submarine cannot surface because the steering and propulsion system is not functioning properly. With the submarine unable to surface, it will cause the ship to sit on the seabed. A submarine that experiences an emergency so that it cannot surface is called a Distressed Submarine (DISSUB). Through the FMEA method the author identifies risks and aims to prioritize different causes based on their priority. FMEA itself is a systematic method, so it can find out the root of the problem that actually occurs. By knowing how urgent the priority is, the author can focus on problems that have a big impact on ship operational risks. It is hoped that the research results can be used as recommendations for mitigating risks that occur on submarines, providing a risk management framework for submarines.

**Keywords**: Distressed Submarine (DISSUB), Failure Mode and Effects Analysis (FMEA), Risk



## INTRODUCTION

Submarines as a strategic weapon system are designed to operate on the surface or below the sea surface.[1] As a vehicle that is required to always operate below sea level, the risks faced by the submarine and its crew are very large. One of the risks that can occur is that the submarine cannot surface because the steering and propulsion system is not functioning properly. With the submarine unable to surface, it will cause the ship to sit on the seabed. A submarine that experiences an emergency so that it cannot surface is called a Distressed Submarine (DISSUB).

There are 2 (two) methods of rescuing the DISSUB crew, namely the rescue method and the

[1] Thahera Yudnina Allim, Supartono Supartono, and Rudy A G Gultom, "Desain Konseptual Sistem Pengawasan Kapal Selam Asing Berbasis Teknologi Akustik Tomografi Untuk Mendukung Sistem Pertahanan Negara," *Teknologi Penginderaan* 1, no. 2 (2019).

escape method. If the rescue method relies on the rescue force's ability to find the DISSUB location and provide assistance, the escape method relies on the knowledge and ability of the DISSUB crew to assess the situation within the DISSUB for decision making. Determining the waiting time limit in DISSUB is influenced by several factors, including carbon dioxide (CO2) level limits, pressure limits and oxygen (O2) level limits (KOARMADA II Submarine Unit Standing Procedure Book (Protap), 2020 ).

Furthermore, if the escape method is chosen to save oneself from DISSUB, then there are 2 (two) escape techniques, namely Rush or Compartment Escape and Tower Escape. These two escape techniques are carried out using Submarine Escape Immersion Equipment (SEIE). After carrying out the rescue from DISSUB, the submarine crew then appeared on the surface and carried out surface survival while waiting for help (Standing Procedure Book (Protap) KOARMADA II Submarine Unit, 2020).

Submarine crew as crew personnel need to develop the ability to carry out escapes, both rush escapes and tower escapes.[2] The capabilities developed include mastery of safety equipment technology, good knowledge and skills of organizational crew personnel, appropriate procedures and supported by the implementation of good and planned training. The good condition of the submarine and the professionalism of the submarine crew are of course an asset in securing Indonesia's seas.

Geographically, Indonesia is an archipelagic country that stretches between the Australian Continent and the Asian Continent and between the Pacific Ocean and the Indian Ocean.[3] In the TNI AL doctrine book, Jales Veva Jaya Mahe, it was found that the number of islands in Indonesia reached 17,504, consisting of large islands and small islands. Indonesia has a coastline of 108,000 km. With the enactment of the UN convention on the law of the sea, namely the United Nations Convention on the Law of the Sea (UNCLOS) 1982, Indonesia has a total land area of 1.9 million km$^2$ and a total water area of 6.4 million km$^2$.[4] If the area of these waters is further broken down into a territorial waters area of 0.29 million km$^2$, an archipelagic waters area of 3.11 million km$^2$, and an Exclusive Economic Zone EEZ area of 3 million km$^2$ (Kasal Decree No Kep-503-V-2018

[2] Faris Al-Fadhat and Naufal Nur Aziz Effendi, "Kerjasama Pertahanan Indonesia-Korea Selatan: Ketahanan Maritim Dan Transfer Teknologi Dalam Pengadaan Kapal Selam DSME 209/1400," *Jurnal Ketahanan Nasional* 25, no. 3 (2019): 373–92; Marsetio Marsetio and Rajab Ritonga, "Representasi Kapal Selam Indonesia Dalam Perspektif Pertahanan Regional," *Jurnal Kajian Stratejik Ketahanan Nasional* 1, no. 2 (2018): 1.

[3] Umar Harun, "Buku: Politik Kebijakan Poros Maritim," 2020; Dwi Ardiyanti, "Indonesia Sebagai Poros Maritim Dunia," *Resolusi: Jurnal Sosial Politik* 1, no. 2 (2018): 132–45.

[4] NUGROHO D W I YULIANTO, "Analisis Perubahan Garis Pantai Di Kabupaten Tuban Tahun 2000, 2015, Dan 2020" (Universitas Gadjah Mada, 2023).

Dated 22 May 2018 Concerning Indonesian Navy Submarines," no. 302 (2018).

Indonesia's maritime territory is so wide and stretches in a cross position between two continents, namely the Asian Continent and the Australian Continent, and is located between two oceans, namely the Indian Ocean and the Pacific Ocean. This geographical location is very strategic because it places Indonesia on international shipping routes, namely Sea Lanes of Communication (SLOC) and Sea Lines on Trade (SLOT) (Wiranto, 2020). Trade routes in Indonesia have been formed naturally over the previous centuries during the kingdoms of the archipelago. Apart from providing benefits, this international shipping route also has other impacts in the form of threats to state sovereignty.

Ability in carrying out sea control, preventing enemy use of the sea (sea denial), blockade and power projection are absolute capabilities that must be possessed by the Indonesian Navy (TNI AL) to be able to support strategy. appropriate defense for Indonesia as an archipelagic country (TNI AL Doctrine "Eka Sasana Jaya", Archipelago Maritime Defense Strategy, Mabasa, Jakarta, 2006).


Figure 1.1. Indonesian Archipelago Sea Lanes

Source : www.ruangguru.com (2023)

The TNI AL's capabilities, as mentioned above, can be realized through planning and building the TNI AL's posture within the framework of an appropriate Integrated Fleet Weapons System (SSAT).[5] Submarines as part of the SSAT component have reconnaissance and infiltration capabilities with a level of difficulty in detection by opponents, as well as ambush and high

[5] Endi Esmoyo, "Pengaruh Teamwork Dan Locus of Control (Loc) Terhadap Kinerja Dopusbektim Dalam Mendukung Kesiapan Logistik Koarmada II," *Jurnal Education and Development* 10, no. 2 (2022): 405–8.

destructive power providing the deterrence effect needed to support the implementation of sea control, sea denial, blockade and power projection. For this reason, it is necessary to develop the strength and pattern of deployment of submarine elements supported by the readiness of advanced infrastructure and base facilities that are in accordance with the characteristics of the Submarine Operating Area (SOA) in order to provide maximum deterrence effect on parties who have the potential to cause harm. threat to upholding sovereignty in national jurisdiction (Defence White Paper, Indonesian Ministry of Defense, Jakarta, 2015).

This is in line with the Indonesian National Army (TNI) Commander's Regulation (Perpang) Number 26/V/2008 concerning Maritime Operations, which states that National Defense at sea as an integral part of national defense is formulated in the form of the Archipelago Maritime Defense Strategy (SPLN) which is based on The concept of archipelagic state defense is basically an effort to ensure the upholding of sovereignty and law throughout Indonesia's national jurisdiction.[6] National defense efforts at sea are achieved through sea control which is carried out with various forms of sea operations, both independent and combined in certain sea areas (TNI Commander in Chief Regulation Number 26/V/2008 concerning Sea Operations).

In this research, the risk management design process goes through the stages of risk identification, risk analysis, risk evaluation, risk management, monitoring and review. In identifying and measuring potential risks the focus is on submarine operations, because the risks faced can be seen in the operational part of the submarine. Operational risk management begins with identifying significant sources of risk during submarine operations, then entering them into a risk register. A risk list is created as an output or result of risk identification. The next step is to assess all the risks that have been identified. In identifying risks using brainstorming, to analyze risks using a risk matrix, to evaluate risks using FMEA (Failure Mode and Effect Analysis) and the final stage is to treat risks through manual calculation of recommendations.

Designing risk management on submarines is very relevant using the House of Risk (HOR) method because this method is a development of the FMEA (Failure Mode and Effect Analysis) method and adapts the HOQ (House of Quality) method to prioritize which risk triggers must be addressed first. first and to select the most effective actions in reducing risks that may arise.

This solution method was developed by Pujawan and Geraldin in 2011. The advantage of this method is that the stages in the framework that have been prepared are included in one

[6] Basri Mustari, Supartono Supartono, and Rayanda Barnas, "Strategi Pertahanan Laut Nusantara Dalam Mewujudkan Indonesia Sebagai Poros Maritim Dunia," *Strategi Perang Semesta* 4, no. 2 (2018).

method that can be used to carry out risk management analysis. In the HOR method, there is an aggregate value of potential risk for each risk agent and most importantly, there is a correlation matrix that influences each risk to obtain mitigation actions that must be taken. HOR is divided into 2 stages, namely the first stage, risk identification, which is the development of the HOQ method based on consumer needs, in this case Indonesia's needs in responding to maritime operations needs. Continued in the second step, risk treatment is the development of the FMEA method which is used to reduce or reduce risk events that will arise in submarine operations.

The risk identification step is the step where risk events and risk triggers are identified, measured and prioritized, then the level of correlation is calculated. Then the risk handling step is a step where the risk agent is selected based on the high priority level of the first step HOR output. After that, formulate relevant actions based on the relationship between each preventive action and each risk trigger (risk agent). The final stage, designing preventive activities as a form of response or risk mitigation.

## METHOD

A qualitative research approach is used in collecting data directly from research subjects, and completing interviews related to risk analysis. Primary data comes from officers serving on the Submarine Command Fleet II. This data is then used to identify current conditions and as initial data in research. Secondary data was obtained from literature, articles, journals and websites on the internet relating to the research carried out including a compilation of regulations and policies related to research. The use of secondary data provides the right choice for researchers who have limited time and resources.

The research subjects were chosen according to the needs for which this manuscript was written, including: Officers who currently and have served on submarines. The research subjects were selected according to their field of expertise with the aim of obtaining a logical level of preference regarding the criteria that influence the operational risk of the submarine that will be studied because at this stratum the officers who are research subjects already have an understanding of risk management.

Data collection is carried out in order to obtain the information needed to achieve goals. The data collection step is intended to obtain valid data, so that the truth of the research results is beyond doubt. Data collection techniques used were interviews, questionnaires and documents. In using data collection methods, researchers will use tools that are guided by interviews, questionnaire guidelines and observation guidelines. Interview guidelines and questionnaires are used to gather information from competent parties. Meanwhile, observation guidelines are used by researchers to determine research steps in carrying out analysis. Based on the problems existing in the research, the research methods that will be used are the Failure Mode and Effect Analysis (FMEA) Method and the Fault Tree Analysis (FTA) Method.

## RESULTS AND DISCUSSION

The history of the Navy began with the formation of the People's Security Agency (BKR) at the PPKI session on 22 August 1945. The BKR then developed into several divisions, where the Marine BKR, one of the initial divisions, covered maritime/ocean areas. The formation of the Maritime People's Security Agency (BKR Laut) on 10 September 1945 by Soekarno's initial cabinet administration became an important milestone for the presence of the Navy in the Unitary State of the Republic of Indonesia which was proclaimed on 17 August 1945. The formation of the BKR Laut was spearheaded by veteran maritime figures who had served in the Koninklijke Marine ranks during the Dutch colonial period and was a Kaigun veteran during the Japanese occupation. Another factor that encouraged the formation of this agency was the potential to carry out Navy functions such as ships and bases, even though at that time the Indonesian Armed Forces had not yet been formed. The formation of the Indonesian military organization known as the People's Security Army (TKR) also spurred the existence of the Marine TKR, which was later better known as the Republic of Indonesia Navy (ALRI), with all the strength and capabilities it possessed.

### Submarine Operational Risk Analysis using the FMEA Method

This FMEA method is carried out to analyze submarine operational risk planning and identify the causes and impacts that occur on each risk of submarine operational readiness. This FMEA method prioritizes completion based on level Severity (Impact), Occurance (Frequency of Events), and Detection (Detection Capability). Thus, the results allow controlling each basic cause of the failure.

When distributing the risk assessment questionnaire which was filled in by several respondents, the researcher included a risk assessment scale to assist respondents in assessing the risk in each variable of submarine operational readiness, namely: (1) Ship Losing Bouyancy, (2) Fire, (3) Leak, and (4) Noxious Gas Poisoning.

### Analyzing Levels Severity (Impact)

Level Severity (Impact) aims to understand the impact of each risk that arises in submarine operations to support the duties of the Indonesian Navy. Severity This is evaluated based on the impact caused by each risk assessment in each submarine operational readiness variable, namely: (1) Ship Losing Bouyancy, (2) Fire, (3) Leak, and (4) Toxic Gas Poisoning. In the previous chapter, a severity scale from 1 to 10 was explained. However, to make it easier for respondents to fill out the questionnaire, in this chapter a scale is used. severity, as follows :

Table 4.3 Scale Severity

| Skor Severity | 1 | 2 - 3 | 4 - 5 | 6 – 7 | 8 - 9 | 10 |
|---|---|---|---|---|---|---|
| Description | Very low | Low | Current ly | Heig ht | Very high | Extreme |

**Source: Data scores processed by the Author (2024)**

Score Severity from the results of the assessment of 7 experts on each risk variable for submarine operational readiness, namely: (1) Ship Losing Bouyancy, (2) Fire, (3) Leaks, and (4) Toxic Gas Poisoning, can be seen in Table 4.4, as follows :

Table 4.4 Severity Score on Research Operational Risk Variables

| Operational Risk | Sub Causes | Severity (S) | Information |
|---|---|---|---|
| **Ship Loses Bouyancy** | Thrust Stopped | 7.80 | Very high |
| | Steering Jammed | 8.00 | Very high |
| | Density of Sea Water | 8.40 | Very high |
| | Internal Solitary Wave | 9.00 | Very high |
| **Fire** | Class A fire | 5.40 | Currently |
| | Class B fire | 4.70 | Currently |
| | Class C fire | 4.80 | Currently |
| | Class D fire | 4.40 | Currently |
| | Class E fire | 4.30 | Currently |
| | Class K fire | 4.50 | Currently |
| **Leakage** | Water Pipe & Valve Systems | 3.70 | Currently |
| | Sea Water System Pump House | 4.20 | Currently |
| **Toxic Gas Poisoning** | Hydrogen | 5.30 | Currently |
| | Lead Acid Battery | 6.00 | Height |

Source: Appendix 2 Expert Data Tabulation (2024)

Table 4.4 shows that the highest severity score is 9.00 for the operational risk of ship loss bouyancy sub cause internal solitary wave in the very high category, meaning that Loss of buoyancy on the submarine due to Internal Solitary Wave is an operational risk with a very high level of severity. Buoyancy is the ability of a submarine to float and control its depth in the water.

Lost buoyancy occurs when a submarine cannot maintain a balance between the weight of the ship and the volume of water it displaces. ISW can cause sudden changes in the pressure distribution and water currents around the submarine, which can disrupt this balance. Here are some potential scenarios: (1) Sudden Depth Change: ISW can cause the submarine to move vertically without control from the crew. This could result in the submarine descending to dangerous depths or rising too quickly to the surface, risking structural damage or dangerous decompression for the crew; (2) Navigation System Disturbance: Strong currents and pressure fluctuations caused by ISW can disrupt a submarine's navigation and control systems. Hydraulic systems, sonar, and other navigation instruments may not function properly, increasing the risk of accidents; and (3) Structural Damage: Uneven water pressure can place excessive loads on the submarine's structure, causing cracks or damage to the hull. This is especially dangerous at greater depths where the water pressure is very high.

In risk assessment using FMEA, the severity level (Severity) describes the potential impact of failure on operations and safety. In the case of loss of buoyancy due to ISW, the severity level can be considered very high for the following reasons: (1) Personnel Safety: Sudden loss of buoyancy can result in an emergency situation that endangers the lives of the crew. The potential for sudden decompression, violent impact with the seabed, or even drowning, places this risk at the highest level of severity; (2) Material Loss: Damage to a submarine can be very expensive and take a long time to repair. This includes damage to the hull, navigation systems, and other equipment vital to submarine operations; (3) Mission Failure: Loss of buoyancy can disrupt or even derail the mission in progress. In military situations, this can mean loss of strategic initiative, failure to gather important intelligence, or inability to provide necessary support; and (4) Strategic Impact: Loss or damage to a submarine has broad strategic implications, including damage to naval power and diplomatic influence. This could also weaken the national defense and security position.

Therefore, it can be said that the impact on personnel safety, material losses, mission success and strategic position is very significant. So a comprehensive and proactive approach is needed to manage this risk. By implementing advanced detection technology, intensively training crews, improving navigation systems, implementing strict operational protocols, and collaborating with international institutions, the Indonesian Navy can increase the operational readiness of submarines and ensure effective support for its strategic tasks.

**Analyzing Levels Occurance (Frequency of Occurrence)**

The frequency of events aims to determine how often failures occur in each operational risk faced by the submarine. This frequency level is based on each risk assessment variable for submarine operational readiness, namely: (1) Ship Loss Buoyancy, (2) Fire, (3) Leak, and (4) Toxic Gas Poisoning. In the previous chapter, a frequency scale from 1 to 10 was explained. However, in this chapter a scale is used Occurance in Table 4.5 to make it easier for respondents to fill out the questionnaire. The following are the frequency scale (occurrence) criteria for each risk of submarine operational incidents.

Table 4.5 Skala Occurance

| Skor Occurrence | 1 | 2 - 3 | 4 - 5 | 6 - 7 | 8 - 9 | 10 |
|---|---|---|---|---|---|---|
| Description | Very rarely | Seldo m | Current ly | Often | Very often | Almost Sure |

Source: Data scores processed by the Author (2024)

Score Occurance from the results of the assessment of 7 experts on each risk variable for submarine operational readiness, namely: (1) Ship Losing Bouyancy, (2) Fire, (3) Leaks, and (4) Toxic Gas Poisoning, can be seen in Table 4.6, as follows :

Table 4.6 Score Occurance on Research Operational Risk Variables

| Operational Risk | Sub Causes | Occurance (O) | Informatio n |
|---|---|---|---|
| **Ship Loses Bouyancy** | Thrust Stopped | 3.70 | Currently |
| | Steering Jammed | 3.70 | Currently |
| | Density of Sea Water | 3.70 | Currently |
| | Internal Solitary Wave | 4.00 | Currently |
| **Fire** | Class A fire | 3.60 | Currently |
| | Class B fire | 3.60 | Currently |
| | Class C fire | 3.70 | Currently |
| | Class D fire | 3.50 | Often |
| | Class E fire | 3.40 | Seldom |
| | Class K fire | 2.70 | Seldom |
| **Leakage** | Water Pipe & Valve Systems | 3.60 | Currently |
| | Sea Water System Pump House | 3.40 | netting |
| **Toxic Gas Poisoning** | Hydrogen | 3.80 | Currently |
| | Lead Acid Battery | 3.20 | Seldom |

Source: Appendix 2 Expert Data Tabulation (2024)

Table 4.6 shows that score Occurance The highest is 4.00 on the operational risk of ship loss bouyancy sub cause internal solitary wave in the Medium category, meaning an occurrence score of 4.00 for the risk of loss of buoyancy due to internal solitary waves shows that even though this event is in the moderate category, the impact can be very dangerous and requires serious attention. In the FMEA analysis, this means that submarine operations must always be prepared to encounter ISW through constant monitoring, intensive training, and the implementation of advanced detection technology. In this way, the Indonesian Navy can minimize risks and ensure mission success and the safety of submarine crews.

**Analyzing Levels Detection (Detection)**

The level of ability to detect submarine operational risks aims to assess how well operational risks can be detected through various submarine operational readiness risk variables, namely: (1) Ship Losing Buoyancy, (2) Fire, (3) Leaks, and (4) Gas Poisoning Poisonous. In the previous chapter, the detection scale from 1 to 10 was explained. However, in this chapter a scale is used detection in Table 4.7 to make it easier for respondents to fill out the questionnaire. The following are the criteria for the detection ability scale (Detection) from any risk of submarine operational incidents.

Table 4.7 Scale Detection

| Score Detection | 1 | 2 - 3 | 4 - 5 | 6 - 7 | 8 - 9 | 10 |
|---|---|---|---|---|---|---|
| Description | Very easy | Easy | Currently | Difficult | Very difficult | Almost impossible |

Source: Data scores processed by the Author (2024)

Score Detection from the results of the assessment of 7 experts on each risk variable for submarine operational readiness, namely: (1) Ship Losing Bouyancy, (2) Fire, (3) Leaks, and (4) Toxic Gas Poisoning, can be seen in Table 4.8, as follows :

Table 4.8 Score Detection on Research Operational Risk Variables

| Operational Risk | Sub Causes | Detection (D) | Information |
|---|---|---|---|
| **Ship Loses Bouyancy** | Thrust Stopped | 3.80 | Currently |
| | Steering Jammed | 3.80 | Currently |
| | Density of Sea Water | 4.10 | Currently |
| | Internal Solitary Wave | 4.20 | Currently |
| **Fire** | Class A fire | 3.60 | Currently |
| | Class B fire | 3.40 | Easy |
| | Class C fire | 3.60 | Currently |
| | Class D fire | 3.30 | Easy |
| | Class E fire | 3.30 | Easy |
| | Class K fire | 3.00 | Easy |
| **Leakage** | Water Pipe & Valve Systems | 3.80 | Currently |
| | Sea Water System Pump House | 3.60 | Currently |
| **Toxic Gas Poisoning** | Hydrogen | 3.90 | Currently |

| | | | |
|---|---|---|---|
| | Lead Acid Battery | 3.90 | Currently |

Source: Appendix 2 Expert Data Tabulation (2024)

Table 4.8 shows that score Detection The highest is 4.00 on the operational risk of ship loss bouyancy sub cause internal solitary wave in the ability category detection moderate, meaning a detection score of 4.00 on the risk of buoyancy loss due to internal solitary waves indicates that even though there are detection systems and procedures, the detection capability is still at a moderate level and requires improvement, in other words that the ability to detect ISW is still at a moderate level . This means that although there are some detection systems available, they may not be effective enough to always provide the necessary early warning.

Linking this to the Standard Operational Procedures for Implementing Emergency Management for Nagapasa Class Submarines, it is important to improve detection technology, strengthen crew training and readiness, and revise SOPs to be more effective. With these steps, the Indonesian Navy can improve its risk detection and mitigation capabilities, thereby ensuring safer and more efficient submarine operations.

**Analyzing RPN (Risk Priority Number) value calculations**

Knowing the most critical risk level by paying attention to various risk scales can be done using the RPN (Risk Priority Number) method. The RPN value is obtained from multiplying the severity, occurrence and detection scales.

$$\boxed{\text{RPN} = \textit{severity x occurance x detection}}$$

The most critical RPN value will be identified as the source of the cause of each risk variable: (1) Ship Loses Buoyancy, (2) Fire, (3) Leak, and (4) Poisoning by Toxic Gas. The RPN value for each risk variable can be seen in Table 4.9 to Table 4.12 as follows:

Table 4.9 RPN of Ship Losing Bouyancy

| Operational Risk | Sub Causes | Severity (S) | Occurance (O) | Detection (D) | RPN |
|---|---|---|---|---|---|
| **Lost Ship *Bouyancy*** | Thrust Stopped | 7.80 | 3.70 | 3.80 | 109.7 |
| | Steering Jammed | 8.00 | 3.70 | 3.80 | 112.5 |
| | Density of Sea Water | 8.40 | 3.70 | 4.10 | 127.4 |
| | Internal Solitary Wave | 9.00 | 4.00 | 4.20 | 151.2 |
| | **Mean** | **8.30** | **3.78** | **3.98** | **124.5** |

Source: Appendix 2 Expert Data Tabulation (2024)

Based on Table 4.9 RPN of Lost Ship Bouyancy value can be known risk priority submarine lost buoyancy above, it is found that repair priorities must take precedence over the operational risk of losing the submarine Bouyancy is Internal Solitary Wave, this is due to the RPN value Internal Solitary Wave highest, compared to Stuck Thruster, Stuck Rudder, and Sea Water Density.

Table 4.10 Fire RPN

| Operational Risk | Sub Causes | Severity (S) | Occurance (O) | Detection (D) | RPN |
|---|---|---|---|---|---|
| **Fire** | Class A fire | 5.40 | 3.60 | 3.60 | 70.0 |
| | Class B fire | 4.70 | 3.60 | 3.40 | 57.5 |
| | Class C fire | 4.80 | 3.70 | 3.60 | 63.9 |
| | Class D fire | 4.40 | 3.50 | 3.30 | 50.8 |
| | Class E fire | 4.30 | 3.40 | 3.30 | 48.2 |
| | Class K Fire | 4.50 | 2.70 | 3.00 | 36.5 |
| | **Mean** | **4.68** | **3.42** | **3.37** | **53.9** |

Source: Appendix 2 Expert Data Tabulation (2024)

Based on Table 4.10, the RPN for Fire values can be determined risk priority above from submarine fires, it was found that the repair priority that must come first from the operational risk of submarine fires is Class A fires, this is because the RPN value for class A fires is the highest, compared to Class B fires, Class C fires, Class D fires, Class A fires. E and Class K Fires.

Table 4.11 RPN Leaks

| Operational Risk | Sub Causes | Severity (S) | Occurance (O) | Detection (D) | RPN |
|---|---|---|---|---|---|
| **Leakage** | Water Pipe & Valve Systems | 3.70 | 3.60 | 3.80 | 50.6 |
| | Sea Water System Pump House | 4.20 | 3.40 | 3.60 | 51.4 |
| | **Mean** | **3.95** | **3.50** | **3.70** | **51.2** |

Source: Appendix 2 Expert Data Tabulation (2024)

Based on Table 4.11 RPN Leakage, the value can be determined risk priority Above, from submarine leaks, it was found that the repair priority that must come first from the operational risks of submarine leaks is the sea water system pump house, this is because the RPN value of the sea water system pump house is the highest, compared to pipe and water valve system leaks.

Table 4.12 RPN of Toxic Gas Poisoning

| Operational Risk | Sub Causes | Severity (S) | Occurance (O) | Detection (D) | RPN |
|---|---|---|---|---|---|
| **Toxic Gas Poisoning** | Hydrogen | 5.30 | 3.80 | 3.90 | 78.5 |
| | Lead Acid Battery | 6.00 | 3.20 | 3.90 | 74.9 |
| | **Mean** | **3.95** | **5.65** | **3.50** | **3.90** |

Source: Appendix 2 Expert Data Tabulation (2024)

Based on Table 4.12 RPN for Toxic Gas Poisoning, the value can be determined risk priority Above, from toxic gas poisoning in submarines, it was found that the priority for improvement that must first be the operational risk of Toxic Gas Poisoning in Submarines is the emergence of hydrogen gas (H2) from lead-acid batteries during processing. charging, this is due to the RPN value of the emergence of hydrogen gas (H2) from the lead-acid battery during the process charging highest, compared to the emergence of toxic gases from lead acid battery electrolyte materials.

Based on value risk priority 4.9 to 4.12 above, it is found that repair priorities must come first from ship operational risks as long as the four causes are ship loss. Bouyancy RPN 124.5, compared to Toxic Gas Poisoning RPN 77.1, Fire RPN 53.9 and Leak RPN 51.2. This RPN value will be connected in the FTA method (Fault Tree Analysis)

**Submarine Operational Risk Analysis using the FTA Method**

Based on the Failure Mode and Effect Analysis (FMEA) carried out, the highest risk of a ship losing buoyancy is due to a phenomenon internal solitary wave. This phenomenon is explained by oceanography experts as strong underwater waves that can pull objects vertically. This internal solitary wave is produced by a combination of strong tidal interactions, temperature differences between warmer and colder sea layers, and underwater geographic conditions.

Furthermore, interviews with experts have identified 14 potential underlying causes (basic event) from the risk of loss of buoyancy in submarines due to internal solitary waves. These potential causes are divided based on human factors, environment and methods. Based on interviews with experts, there are 14 potential causes which are item basic, namely:

| No. | Ship Incident Loss of Buoyancy | Item Basic Event |
|---|---|---|
| 1 | Internal Solitary Wave | **1. Lack of Crew Knowledge and Experience**: Lack of understanding of the internal solitary wave phenomenon and how to deal with it. |
| 2 | | **2. Non-compliance with Operational Procedures**: Crew does not comply with established standard operating procedures. |
| 3 | | **3. Fatigue and Stress**: Crew experiences fatigue or stress which can affect decisions taken. |
| 4 | | **4. Poor Communication**: Lack of communication between crew in emergency situations. |
| 5 | | **5. Inadequate Training**: The training provided is not sufficient to deal with critical situations such as internal solitary waves. |
| 6 | | **6. Rapid Changes in Sea Conditions**: A sudden and unexpected change in sea conditions. |
| 7 | | **7. Influence of Climate and Weather**: Extreme weather conditions that worsen the situation at sea. |
| 8 | | **8. Diversity of Undersea Geography**: A complex underwater structure that amplifies the effects of internal solitary waves. |
| 9 | | **9. Ocean Current Conditions**: Strong and unpredictable |

| No. | Ship Incident Loss of Buoyancy | Item Basic Event |
|---|---|---|
| | | ocean currents. |
| 10 | | **10. Errors in Navigation**: An error in navigation that causes a ship to enter a high-risk area. |
| 11 | | **11. Deficiencies in the Detection and Monitoring System**: Detection and monitoring system that cannot detect internal solitary waves effectively. |
| 12 | | **12. Ineffective Evacuation Procedures**: Evacuation procedures that cannot be carried out quickly and efficiently. |
| 13 | | **13. Lack of Alarm and Early Warning Systems**: The absence or malfunction of an alarm system that can warn the crew of approaching danger. |
| 14 | | **14. Obsolete Ship Technology**: Ship technology is outdated and unable to deal with extreme sea conditions. |

Source: Interview with Expert (2024)

**Tree diagram Fault Tree Analysis (FTA)**

Tree diagram Fault Tree Analysis (FTA) for the event of a ship losing buoyancy due to the internal solitary wave phenomenon which has been discussed with experts. This diagram shows the flow from top events to intermediate events and then to basic events, using AND gate and OR gate symbols to describe the relationship between events.

## Discussion

Based on Failure Mode and Effect Analysis (FMEA) and Fault Tree Analysis (FTA), this research identified that the main factor causing submarines to lose buoyancy is the internal solitary wave (ISW) phenomenon. In the FMEA analysis, ISW has the most dominant Risk Priority Number (RPN) value, indicating that this threat is a significant operational risk for submarines. The Fault Tree Analysis (FTA) diagram shows the flow relationship from top event, namely the ship losing buoyancy, to intermediate events and basic events, with the use of AND gates and OR gates to describe the relationship between events.

Study by Wang, et al. (2022) provide strong support for these findings by analyzing the characteristics and impacts of ISWs in the Bali Sea and linking them to the KRI Nanggala-402 accident. Some key points from the study of Wang et al. relevant to the findings from FMEA and FTA include the identification of active ISWs in the Bali Sea with a peak length of close to 200 km, which moves from the Lombok Strait to the northwest across the Bali deep sea basin. This analysis reinforces the finding that ISWs are a significant real threat to submarine navigation, especially in areas identified as high risk areas. In addition, the study of Wang et al. linked the KRI Nanggala-402 accident to ISWs that had large amplitudes and high propagation speeds in the area where the submarine sank, confirming that ISWs can cause sudden changes in buoyancy, which was identified as a major risk factor in the FMEA and described in the FTA as intermediate event that leads to loss of buoyancy.

Combining these findings provides a comprehensive understanding of the threat posed by ISWs to submarine operations in Indonesian territory, particularly in the Bali Sea. Some points of this integration include the theory of ISWs which explains that ISWs are non-linear internal waves that can move through layers of water at quite large speeds and amplitudes, capable of affecting the stability of submarines. Understanding these mechanisms helps develop effective mitigation strategies to reduce risk. Specific observations in the Indonesian region using data from satellite imagery enable real-time identification and monitoring of ISWs. Observations in the Bali Sea show that ISWs in this region have characteristics that can cause submarine accidents, such as what happened to the KRI Nanggala-402. The case study of KRI Nanggala-402 provides practical insight into how ISWs can cause buoyancy loss in submarines.

By combining theory about ISWs, specific observations in the Indonesian region, and analysis of the impact of ISWs on submarine navigation, this study provides a comprehensive understanding of the threat posed by ISWs to submarine operations in the Bali Sea. The findings from the FMEA and FTA analyzes indicating ISWs as a major risk factor were strengthened by an empirical study by Wang et al. (2022), provides a strong basis for the development of effective mitigation strategies in supporting the duties of the Indonesian Navy. This mitigation strategy includes increasing crew training and education, strengthening ship systems and technology, as well as comprehensively handling environmental factors. By implementing these mitigation measures, the risk of loss of buoyancy on submarines due to internal solitary waves can be minimized, thereby supporting the smooth and safe operation of the Indonesian Navy.

## CONCLUSION

Identification of operational risks on submarines can be done using the Failure Mode and Effect Analysis (FMEA) and Fault Tree Analysis (FTA) approaches. Through FMEA, various potential failures are identified and analyzed to determine the Risk Priority Number (RPN) value, which indicates the severity, probability of occurrence, and detection ability of each risk. The internal solitary wave (ISW) phenomenon was identified as the main factor causing loss of buoyancy in submarines, having the most dominant RPN value. In FTA, this risk is analyzed further by describing the flow relationship from top event, intermediate event, to basic event, using AND gate and OR gate symbols to show how various factors contribute to this significant operational risk.

The assessment and evaluation of risk events on submarines involves in-depth analysis using FMEA and FTA. In FMEA, each potential failure is scored based on severity, likelihood of occurrence, and detectability, resulting in an RPN value that helps identify priority risks that need to be addressed. The analysis results show that ISW is the main operational threat to submarines. FTA completes this evaluation by mapping the flow of events from top events (the ship loses buoyancy) through intermediate events (such as crew unpreparedness and extreme environmental conditions) to basic events (such as lack of crew knowledge and experience, rapid changes in sea conditions, and errors in navigation). . This allows a more comprehensive understanding of how and why these risks occur.

Determining mitigation or handling of submarine risks requires a strategy based on findings from FMEA and FTA. By identifying ISW as a key risk factor, effective mitigation measures can be designed and implemented. Recommended mitigation strategies include increasing training and education for crew to deal with ISW, strengthening submarine systems and technology for real-time ISW detection and response, as well as developing better operational procedures. In addition, implementing alarm and early warning systems that can detect ISW effectively, as well as improving ship technology to be able to face extreme sea conditions, is also very important. This comprehensive approach aims to minimize the risk of loss of buoyancy on submarines, thereby supporting the Indonesian Navy's operational tasks more safely and effectively.

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