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# Operational Risk Assessment of a 150,000 DWT Single Buoy Mooring

**Muhammad Bayu Abisatya[a*], Silvianita[a], Daniel Mohammad Rosyid[a]**

[a)] Department of Ocean Engineering, Faculty of Marine Technology, Institut Teknologi Sepuluh Nopember, Surabaya, Indonesia
*Corresponding author: bayu.abisatya@gmail.com

## ABSTRACT

*Single Buoy Mooring (SBM) is a critical offshore facility used for tanker berthing and fluid transfer in oil and gas distribution systems, where complex interactions between vessels, mooring components, mechanical equipment, and dynamic marine environments generate significant operational risks. This study assesses the operational risks of a 150,000 DWT SBM system using a semi-quantitative Hazard Identification, Risk Assessment, and Risk Control (HIRARC) approach integrated with expert judgment. Hazard identification was conducted across all operational stages, including approaching, mooring, fluid transfer, and departing. Risk assessment was performed by evaluating the Likelihood of Failure (LoF) and the Consequence of Failure (CoF), with CoF assessed across safety, environmental, and asset/operational dimensions. Risk ranking employed a worst-case approach by selecting the maximum risk value among the three dimensions. The results indicate that hazards related to mooring chain integrity, pretension control, and swivel sealing systems present high to very high-risk levels. Further analysis using Bow-Tie Analysis highlights escalation pathways and the effectiveness of existing control barriers. The study demonstrates that the integrated HIRARC and Bow-Tie framework provides a practical basis for prioritizing operational risk controls in large-capacity SBM systems under limited historical failure data.*

**Keywords:** *Bow-tie analysis; HIRARC; Operational risk; Single buoy mooring; Offshore facility.*

## 1. INTRODUCTION

Single Buoy Mooring (SBM) is an offshore facility used for tanker berthing and fluid transfer in oil and gas distribution systems. Its operation involves complex interactions between mooring components, mechanical equipment, fluid transfer systems, and dynamic marine environmental conditions, generating significant operational risks affecting safety, environmental protection, and operational continuity [1], [2].

Operational failures in SBM systems may result in severe consequences, including personnel injury, hydrocarbon spills, and disruption of terminal operations leading to asset damage and downtime. These risks are amplified in large-capacity SBM facilities, such as 150,000 DWT systems, due to higher operational loads and transfer volumes [2] [3]. Single buoy mooring 150.000 DWT as shown in Figure 1.

Figure 1 Single Buoy Mooring 150.000 DWT

The application of fully quantitative risk assessment for SBM operations is often constrained by limited historical failure data and site-specific operating conditions. Therefore, semi-quantitative approaches incorporating expert judgment are more appropriate for representing operational risks in offshore mooring systems [3], [4]. The Hazard Identification, Risk Assessment, and Risk Control (HIRARC) method provides a structured framework for identifying hazards, evaluating likelihood and consequences, and prioritizing risk control measures [5], [6].

This study aims to assess the operational risks of a 150,000 DWT Single Buoy Mooring system using a HIRARC-based approach integrated with expert judgment and Bow-Tie Analysis to support prioritized operational risk control strategies [6], [7].

## 2. METHODOLOGY

### 2.1 Hazard Identification in Single Buoy Mooring Operations

Hazard identification is conducted as the initial stage of the risk assessment process, focusing on operational activities of the SBM system. The identification process considers the full sequence of SBM operations, including tanker approaching, mooring, fluid transfer, and departing. Hazards are identified based on potential sources of mechanical energy, material degradation, operational deviation, and environmental loading that may lead to failure scenarios during normal or abnormal operations.

This operationally driven hazard identification approach ensures that the identified hazards represent realistic failure mechanisms associated with SBM systems and provides a structured foundation for subsequent likelihood and consequence evaluation [1], [2]

### 2.2 Expert Judgment

Due to limited availability of comprehensive historical failure data for offshore mooring systems, expert judgment is adopted as the primary input for risk assessment. Expert judgment incorporates the experience and practical knowledge of professionals involved in SBM design, operation, inspection, maintenance, and safety management.

This approach allows the assessment to reflect site-specific conditions, cumulative degradation mechanisms, and operational practices that are not fully captured in formal datasets. The use of expert judgment is widely applied in offshore risk analysis and is considered appropriate for semi-quantitative risk evaluation of complex systems such as SBM facilities [2].

### 2.3 HIRARC Risk Assessment

The Hazard Identification, Risk Assessment, and Risk Control (HIRARC) framework is used as the main analytical structure to evaluate operational risks. Within this framework, identified hazards are assessed by combining the likelihood of failure and the severity of potential consequences.

Likelihood assessment is based on expert evaluation of failure occurrence tendency, while consequence assessment considers the severity of impacts across three dimensions: safety, environment, and asset/operation. This multidimensional approach ensures balanced consideration of personnel safety, environmental protection, and operational continuity in SBM operations [4]

### 2.4 Likelihood of Failure and Consequence of Failure Scales

The likelihood of failure is quantified using a Likelihood Index (LI), calculated from the distribution of expert responses. The LI formulation provides a normalized measure of relative failure probability among identified hazards.

$$LI = \frac{\sum_{i=1}^{n} a_i \, X \, n_i}{5N} \, X \, 100\% \quad (1)$$

$a_i$ = *likelihood score at level i (Likert scale 1–5)*
$n_i$ = *number of respondents assigning likelihood score $a_i$*
$N$ = *total number of respondents*

To enable semi-quantitative evaluation, LI values are converted into discrete Likelihood of Failure (LoF) scores using predefined classification criteria as in Table 1.

Table 1 Likelihood Index Conversion to Likelihood of Failure Score

| Score | ranking |
|---|---|
| 0% < L.I ≤ 20% | 1 |
| 20% < L.I ≤ 40% | 2 |
| 40% < L.I ≤ 60% | 3 |
| 60% < L.I ≤ 80% | 4 |
| 80% < L.I ≤ 100% | 5 |

The consequence of failure is evaluated using a Severity Index (SI), which reflects the relative severity of impacts based on expert judgment. SI values are calculated separately for safety, environmental, and asset/operational dimensions.

$$SI = \frac{\sum_{i=1}^{n} a_i \, X \, n_i}{5N} \, X \, 100\% \quad (2)$$

$a_i$ = *likelihood score at level i (Likert scale 1–5)*
$n_i$ = *number of respondents assigning likelihood score $a_i$*
$N$ = *total number of respondents*

SI values are subsequently converted into Consequence of Failure (CoF) scores using predefined consequence classification criteria, as in Table 2

Table 2. Severity Index Conversion to Consequence of Failure Score

| Score | ranking |
|---|---|
| 0% < S.I ≤ 20% | 1 |
| 20% < S.I ≤ 40% | 2 |
| 40% < S.I ≤ 60% | 3 |
| 60% < S.I ≤ 80% | 4 |
| 80% < S.I ≤ 100% | 5 |

### 2.5Risk Matrix and Risk Ranking Principle

Risk evaluation is performed by combining the Likelihood of Failure (LoF) and Consequence of Failure (CoF) scores within a risk matrix framework. The risk matrix provides a visual and analytical tool to classify risk levels and support prioritization of risk control measures.

Risk values are calculated separately for safety, environmental, and asset/operational dimensions. To ensure that the most critical potential impact is adequately represented, a worst-case principle is applied by selecting the maximum risk value among the three consequence dimensions as the overall risk level for each hazard [5]

### 2.6 Bow-Tie Analysis

Bow-Tie Analysis is applied as a complementary method to further analyse hazards identified as having the highest risk levels. The Bow-Tie framework integrates fault-oriented and consequence-oriented perspectives by mapping threats, preventive barriers, escalation factors, consequences, and mitigative barriers associated with a top event.

This method supports a deeper understanding of risk escalation pathways and provides a structured basis for evaluating the adequacy of existing technical and operational controls in SBM operations [6]

## 3. RESULT AND DISCUSSIONS

### 3.1 Operational Hazard Characteristics in SBM Systems

The hazard identification results indicate that operational risks in the Single Buoy Mooring (SBM) system are dominated by hazards related to mechanical integrity and load control mechanisms. Hazards associated with mooring chain degradation, pretension deviation, and dynamic tanker–SBM interaction emerge as the most critical, reflecting continuous exposure to cyclic loading, environmental forces, and operational variability. These findings confirm that SBM operational risks are primarily driven by progressive degradation and system interaction rather than isolated procedural failures, providing a clear basis for subsequent likelihood and consequence evaluation, as shown in Table 3. The distribution of identified hazards across operational stages provides essential context for interpreting the likelihood assessment results discussed in the following section.

### 3.2 Likelihood of Failure Characteristics

The likelihood assessment shows clear differentiation among identified hazards, with higher Likelihood of Failure (LoF) values observed for hazards related to mooring chain integrity and pretension control. This pattern reflects expert perception that these hazards are persistently exposed to mechanical and environmental stresses throughout SBM operations, increasing failure probability over time. Conversely, hazards associated with abnormal or infrequent events tend to exhibit lower likelihood values, although their potential impacts remain significant. The calculated Likelihood Index (LI) values and corresponding LoF scores for each hazard are summarized in Table 4.

Table 3. Single Buoy Mooring Hazard Identification

| No | Work Stage | Potential Hazard | | Hazard | Hazard Type | Hazard Effect |
|---|---|---|---|---|---|---|
| | | Unsafe Condition | Unsafe Action | | | |
| Survival Condition | | | | | | |
| 1 | In-service inspection | Corrosion and wear of mooring chains | Inspection not performed according to specified intervals or procedures | Degradation of mooring chain material | Mechanical | Loss of mooring capacity and increased probability of chain failure |
| Tanker Approaching Condition | | | | | | |
| 2 | Tanker berthing / mooring | High tension on hawser and snap-back area | Personnel present within snap-back zone during mooring | High tensile energy on hawser during mooring operations | Mechanical | Hawser rupture, serious personnel injury, and operational disruption |
| 3 | Tanker berthing / mooring | Quick release hook mechanism not responsive | Delayed activation of emergency release | Limited reliability of quick release hook system | Mechanical | Failure of emergency release leading to increased collision risk |
| … | … | …. | … | … | … | … |
| Transfer Operation Condition | | | | | | |
| 8 | Routine swivel / rotating head operation | Wear of swivel bearing and sealing components | Inadequate condition monitoring | Reliability issues of swivel and rotating joint sealing system | Mechanical / Environmental | Fluid leakage, environmental contamination, and increased fire hazard |
| … | … | … | … | … | … | … |
| Tanker Departing Condition | | | | | | |
| 12 | Lifting & section replacement | Stored tensile energy in hawser / chain | Personnel present in the work area during release | Lifting and handling of heavy components during departing/maintenance | Mechanical | Personnel injury and damage to critical equipment |
| … | … | … | … | … | … | … |

Table 4. Likelihood Index and Likelihood of Failure scores

| No | hazard | Score Distribution (1 - 5) | | | | | LI (%) | L Score |
|---|---|---|---|---|---|---|---|---|
| | | 1 | 2 | 3 | 4 | 5 | | |
| Survival | | | | | | | | |
| 1 | Degradation of mooring chain material | 1 | 1 | 6 | 5 | 1 | 65.7 | 4 |
| Tanker Approaching | | | | | | | | |
| 2 | High tensile energy on hawser during mooring operations | 2 | 2 | 7 | 3 | 0 | 55.7 | 3 |
| 3 | Limited reliability of quick release hook system | 2 | 8 | 3 | 1 | 0 | 44.3 | 3 |
| … | … | … | … | … | … | … | … | … |
| Transfer Operation Condition | | | | | | | | |
| 8 | Reliability issues of swivel and rotating joint sealing system | 1 | 1 | 8 | 3 | 1 | 62.9 | 4 |
| … | … | … | … | … | … | … | … | … |
| Tanker Departing Condition | | | | | | | | |
| 12 | Lifting and handling of heavy components during departing/maintenance | 2 | 2 | 10 | 0 | 0 | 51.4 | 3 |
| … | … | … | … | … | … | … | … | … |

While likelihood provides insight into failure tendency, it does not fully represent risk severity without considering the magnitude of potential consequences, which is addressed in the following subsection.

### 3.3 Consequence of Failure Across Impact Dimensions

The consequence assessment demonstrates that dominant impact dimensions vary depending on hazard characteristics. Safety consequences are most pronounced for hazards involving the release of stored mechanical energy, such as snap-back events and mooring line failures, which pose direct risks to personnel. Environmental consequences are more dominant for hazards associated with fluid transfer and sealing systems due to the potential for hydrocarbon spills, while asset and operational consequences are highest for failures involving critical SBM components that may result in extended downtime and equipment damage. A comparative summary of Consequence of Failure (CoF) values across safety, environmental, and asset/operational dimensions is presented in Table 5.

Table 5. Consequence of Failure values by dimension

| Kode | Hazard | CoF Safety | CoF Env | CoF Asset |
|---|---|---|---|---|
| 1 | Degradation of mooring chain material | 3 | 4 | 5 |
| 2 | High tensile energy on hawser during mooring operations | 3 | 4 | 4 |
| 3 | Limited reliability of quick release hook system | 4 | 4 | 4 |
| … | … | … | … | … |
| 8 | Reliability issues of swivel and rotating joint sealing system | 3 | 4 | 4 |
| … | … | … | … | … |
| 12 | Lifting and handling of heavy components during departing/maintenance | 3 | 3 | 3 |
| … | … | … | … | … |

The multidimensional nature of consequences highlights the need to integrate likelihood and consequence results to determine overall risk priorities.

### 3.4 Risk Ranking and Priority Hazards

The risk ranking results indicate that hazards related to mooring chain integrity, pretension deviation, and uneven load distribution consistently occupy the highest risk categories. These hazards combine relatively high likelihood values with severe consequences across multiple impact dimensions, justifying their prioritization for risk control measures. The application of a worst-case approach ensures that the most critical potential impact governs overall risk classification. The overall risk ranking per hazard is summarized in Table 6, while the distribution of hazards across risk levels is illustrated in Table 7.

Table 6. Risk ranking Calculation results

| No. | Hazard | LoF | CoF Safety | CoF Env | CoF Asset | R_max |
|---|---|---|---|---|---|---|
| 1 | Degradation of mooring chain material | 4 | 3 | 4 | 5 | 20 |
| 2 | High tensile energy on hawser during mooring operations | 3 | 3 | 4 | 4 | 12 |
| 3 | Limited reliability of quick release hook system | 3 | 4 | 4 | 4 | 12 |
| … | … | … | … | … | … | … |
| 8 | Reliability issues of swivel and rotating joint sealing system | 4 | 3 | 4 | 4 | 16 |
| … | … | … | … | … | … | … |
| 12 | Lifting and handling of heavy components during departing/maintenance | 3 | 3 | 3 | 3 | 9 |
| … | … | … | … | … | … | … |

A graphical representation of the risk distribution provides additional clarity for prioritization and decision-making. The risk matrix highlights a limited number of hazards that require immediate attention due to their high or very high-risk classification.

Table 7 Risk Matrix

| likelihood | | Consequence | | | | |
|---|---|---|---|---|---|---|
| | | Negligible | Minor | Moderate | Major | Severe / Catastrophic |
| | | 1 | 2 | 3 | 4 | 5 |
| Rare | 1 | - | - | - | - | - |
| Unlikely | 2 | - | - | - | - | - |
| Possible | 3 | - | - | 12 | 2, 3, 5, 6, 7, 9, 10, 11, 13 | - |
| Likely | 4 | - | - | - | 4, 8 | 1 |
| Frequent | 5 | - | - | - | - | - |

### 3.5 Bow-Tie Analysis

Bow-Tie Analysis applied to the highest-ranked hazards reveals that risk escalation is influenced not only by technical degradation mechanisms but also by the effectiveness of operational and organizational barriers. Weaknesses in preventive controls, such as inspection accuracy and monitoring reliability, are identified as key contributors to increased likelihood, while the adequacy of mitigative measures, including emergency response procedures and operational restrictions, plays a critical role in limiting consequences. A summary of the Bow-Tie

Table 8 Bow-Tie Analysis Threat and Preventive barrier

| Top Event | Threat | Preventive Barrier | Escalation Factor |
|---|---|---|---|
| Failure of mooring chain material integrity | Marine environmental corrosion and pitting | Cathodic protection, coating, scheduled inspections | Degraded protection, ineffective inspection, marine growth |
| | Fatigue due to cyclic loading | NDT inspection, condition-based maintenance | Inaccurate inspection location, human error |
| | Overload due to improper pretension or line-length setting | Pretension verification, load monitoring | Procedural deviation, inaccurate instrumentation |
| | Extreme environmental loading | Weather criteria, go/no-go decision | Rapid weather changes, limited metocean data |
| | Material or manufacturing defects | Material QA/QC, baseline inspection | Invalid certification, inadequate acceptance inspection |
| | Maintenance human error | SOP implementation, training, audits | High workload, deferred maintenance culture |

Analysis results is split into 2 table, Table 8 is threats and its barrier, and table 9 is consequence and its barrier.

Table 9 Bow-Tie Analysis Consequence and Mitigative Barrier

| Top Event | Consequence | Mitigative Barrier | Escalation Factor |
|---|---|---|---|
| Failure of mooring chain material integrity | Mooring chain rupture | Redundant Mooring Legs | Common-cause degradation across mooring legs |
| | Buoy drift / loss of mooring position | Stand-by tug, safety zone enforcement | Delayed detection and response initiation |
| | Collision with Tankers or Risers | Tug Intervention | Limited tug availability or adverse weather |
| | Enviroment Impact | OSCP (Oil Spill Contingency Plan) Deployment | Logistic delay and equipment readiness |
| | Operational downtime and asset loss | Contingency planning, risk-based repair prioritization | Long procurement lead time |

The visual representation of the Bow-Tie diagram clarifies escalation pathways and identifies specific points where strengthening existing barriers can effectively reduce overall operational risk. Figures of Bow-Tie Analysis will be split in 2 Figures, Figure 2 is Threats and Figure 3 Is Consequence. Figure 2 is the left side of the Bow-Tie Analysis shown below.

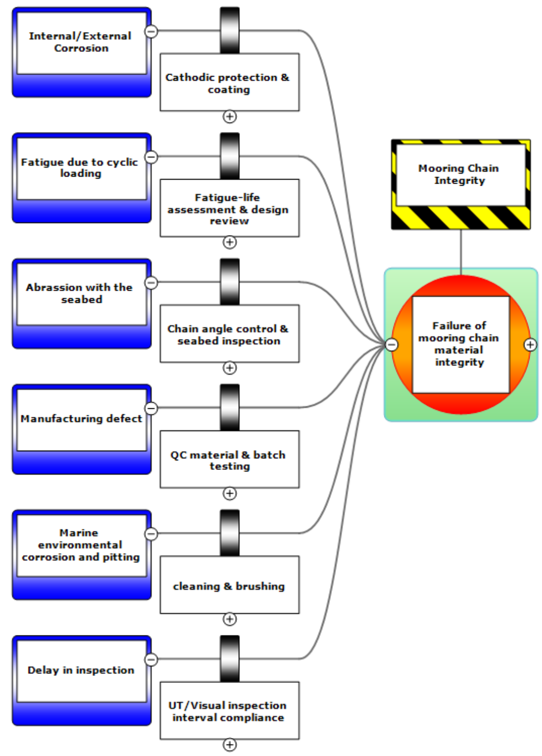


Figure 2. Visual Result of Bow-Tie Analysis (Threat)

Consequence is the right side of the Bow-Tie analysis, it is shown in Figure 3 below

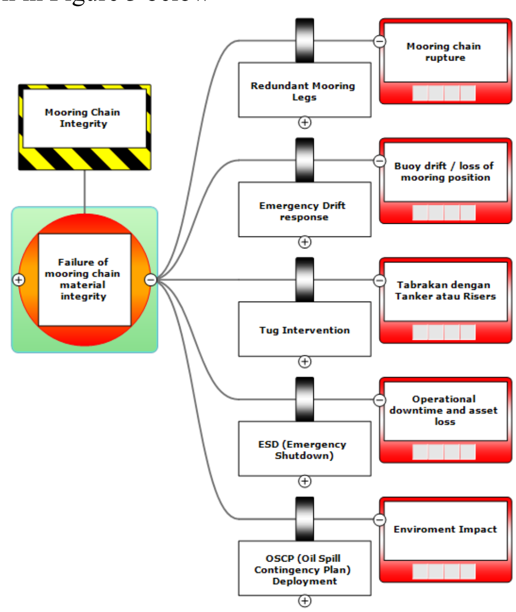


Figure 3. Visual Result of Bow-Tie Analysis (Consequence)

## 4. CONCLUSION

1. The operational risk assessment shows that hazards related to mooring chain integrity, pretension control, and load distribution constitute the most critical risks in the 150,000 DWT Single Buoy Mooring system due to the combination of high likelihood and severe consequences.
2. The semi-quantitative HIRARC approach integrated with expert judgment effectively captures operational risk characteristics under conditions of limited historical failure data and strong site-specific influences.
3. Multidimensional consequence evaluation demonstrates that SBM operational risks cannot be represented by a single impact category, as safety, environmental, and asset/operational consequences dominate different hazard types.
4. The application of Bow-Tie Analysis provides additional insight into risk escalation pathways and highlights the importance of strengthening preventive and mitigative barriers to improve overall SBM operational safety and reliability.

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