Analysis of the Influence of Human and Technical Factors in Mooring Rope Accidents on Ship Operations at Ports of Indonesia

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Analysis of the Influence of Human and Technical Factors in Mooring Rope Accidents on Ship Operations at Ports of Indonesia

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Abstract. Ship mooring operations at the port are one of the critical activities on board a ship that involves the use of mooring lines to secure the position of the ship while at the dock. This study aims to identify various human and technical factors that contribute to mooring line accidents during ship operations at the port, evaluating how effective the safety management system implemented in Indonesian ports. This study uses a mixed method approach regarding the influence of human and technical factors in mooring line accidents on ship operations at the port. The study population includes all personnel involved in ship mooring operations at four ports in Indonesia. The results show that operational time pressure has a strong total effect (0.73) on communication errors through the mechanism of fatigue. In addition, a weak safety culture contributes significantly to material failure (0.60) through inadequate maintenance. The strong correlation between lack of training and inadequate maintenance (r=0.56) shows how deficiencies in personnel competence can impact the technical aspects of mooring operations. The high correlation between fatigue and operational time pressure (r=0.71) highlights the impact of efficiency demands on the physical and mental condition of workers. the development of standardized communication protocols and mandatory pre-operational briefings can be an effective strategy to mitigate the risk of mooring line accidents in the short term, while in the long term, a combination of technical, operational, management and regulatory interventions are needed to comprehensively address the risk factors.

Keywords: Accidents, Communication Protocols, Mooring Line, Technical Factors.

1. Introduction

Ship mooring operations at ports are one of the critical activities on board ships that involve the use of mooring lines to secure the position of the ship while at the dock. Although it seems like a routine procedure, this activity has significant potential hazards to the safety of ship crews, port workers, and maritime infrastructure. Global statistics show that mooring line-related accidents are still the main cause of serious injuries and even deaths while working on ships [1] around 20% of all accident claims involve crew injuries during ship mooring operations, with consequences that are often fatal.

The physical characteristics of mooring lines that have high tensile strength, large size, and the ability to store large potential energy when under tension, create dangerous risks when material failure occurs. The "snap-back" phenomenon occurs when the rope breaks suddenly and can cause a destructive impact at speeds of up to 800 km/h [2]. In addition to technical factors in the form of material failure, the human factor also plays a significant role in the causes of mooring rope accidents. Poor communication, fatigue, lack of training, and non-compliance with safety procedures are the causal elements that are often identified in accident investigations [3], [4], [5].

The problem of mooring line accidents has become increasingly complex in the modern era with the increasing size of ships requiring stronger mooring lines and the ability to handle them, while on the other hand there is a limited number of crew due to automation [6], [7]. The imbalance between operational needs and the availability of competent human resources creates additional pressure that has the potential to pay less attention to safety aspects in mooring operations.

Indonesia as an archipelagic country with thousands of ports serving various types and sizes of ships, the problem of mooring line safety is an issue that requires special attention [8], [9]. The diversity of port infrastructure, from modern to traditional, creates variations in the safety standards applied. Based on data from the National Transportation Safety Committee (KNKT), throughout the 2015-2020 period, 23 accidents related to mooring operations were recorded with severity levels ranging from minor injuries to fatalities [10].

Several previous studies conducted by [11], mooring rope accidents are one of the main causes of injury and death on ships, with a fatality rate reaching 10-15% of total maritime accidents. Their study analyzed 142 cases of mooring rope accidents during the period 2008-2016 and found that mooring rope breaks due to overload accounted for almost 60% of all incidents.

An investigation conducted by [12] into the factors causing mooring rope accidents highlighted the importance of crew training and understanding of dynamic loads. Their results showed that almost 45% of accidents were caused by procedural errors and lack of knowledge about the characteristics of the mooring rope used. Ritchie and Lee also identified that modern mooring rope materials, although stronger, have different elongation characteristics than traditional ropes, which are often misunderstood by ship crews.

A comprehensive study conducted by [13] revealed that sudden changes in environmental conditions, such as tidal movements, extreme weather changes, and the influence of other vessels' movements around the port area, contribute significantly to mooring line accidents. The report analyzed 87 mooring line accident incidents in major ports in Asia and Europe, concluding that 37% of the accidents occurred during adverse weather conditions or extreme tidal changes. [14] conducted a systematic analysis of the design and configuration of ship mooring systems, focusing on load distribution and mooring line angles. Their study revealed that suboptimal mooring line configurations can increase the risk of accidents by up to 28%. These findings emphasize the importance of mooring planning that takes into account vessel characteristics, port conditions, and weather forecasts.

Studies on mooring line accidents have tended to focus on technical aspects such as material and equipment failure [15], [16]. Although important, this approach has not comprehensively integrated the influence of human factors that play a role in the chain of accident events. The complex interaction between technical and human factors creates latent conditions that can develop into serious accidents if not properly identified and mitigated.

This study attempts to fill this gap by conducting a systematic analysis of the influence of human and technical factors on mooring line accidents, especially in the context of port operations in Indonesia. An in-depth understanding of the interaction of these two factors is expected to be the basis for developing effective mitigation strategies to improve the safety of ship mooring operations.

This study aims to identify various human and technical factors that contribute to mooring line accidents during ship operations at ports, analyze how these two factors interact with each other in a series of accident events, evaluate how effective the safety management system implemented in Indonesian ports.

2. METHODS

This study uses a mixed method approach that integrates quantitative and qualitative analysis to gain a comprehensive understanding of the influence of human and technical factors on mooring line accidents on ship operations in ports. This approach was chosen because the complexity of the phenomenon studied requires in-depth exploration of causal aspects as well as statistical measurements to identify patterns and trends [17].

The research design adopts an explanatory sequential design model that is implemented in two main phases. The first phase is the collection and analysis of quantitative data through surveys and secondary data analysis, while the second phase is the collection and analysis of qualitative data through in-depth interviews and field observations. The results of the first phase will be used to design the data collection protocol in the second phase, allowing for deeper exploration of significant quantitative findings.

The research will be conducted in four major ports in Indonesia selected based on criteria of ship traffic volume, variety of ship types served, and historical safety records. The four ports are Tanjung Priok Port (Jakarta), Tanjung Perak Port (Surabaya), Makassar Port, and Belawan Port.

The study population includes all personnel involved in ship mooring operations at the four selected ports, including ship crews, port officers, and safety managers. The research sample will be selected using stratified random sampling techniques for the quantitative phase and purposive sampling for the qualitative phase. In the quantitative phase, the sample size is calculated using the Slovin formula with a 95% confidence level and a 5% margin of error, resulting in a target of 341 respondents.

The sample will be stratified based on roles in mooring operations (ship crew, port officers, deck officers), port type, and work experience. For the qualitative phase, 40 participants will be selected purposively based on the results of quantitative data analysis, taking into account the representation of various stakeholder groups.

The data collected in this study were analyzed using complementary quantitative and qualitative methods to gain an in-depth understanding of the factors that influence mooring line accidents. The quantitative analysis began with descriptive statistics that calculated frequencies, distributions, and measures of central tendency to map how frequently various risk factors appeared in the data. This method provided an initial picture of the most common factors contributing to mooring line accidents in the ports studied.

This combination of quantitative and qualitative analysis methods allows researchers to build a comprehensive understanding of the complexity of factors contributing to mooring line accidents, not only identifying what these factors are and how frequently they occur, but also how these factors relate to each other, interact and are perceived by those directly involved in mooring operations at the port.

3. Result

3.1 Identification of Mooring Rope Accident Risk Factors\

This study successfully identified the main risk factors contributing to mooring line accidents in ship operations at ports. Based on the analysis of quantitative data from 341 respondents and qualitative data from 40 in-depth interview participants and observations at four major ports in Indonesia, it was found that risk factors can be grouped into four main categories: human factors, technical factors, organizational factors, and environmental factors. Table 1 presents the frequency distribution and percentage of risk factors identified in mooring line accidents based on the analysis of 87 accident reports that occurred during the period 2018-2023 at the four ports studied.

Table 1. Frequency Distribution of Mooring Line Accident Risk Factors (2018-2023)

Category	Specific Risk Factors	Freq	(%)
Human Factors	Communication error	62	71.3
	Fatigue	51	58.6
	Lack of training	48	55.2
	Unsafe positioning	39	44.8
	Not following procedures	37	42.5
Technical Factors	Rope material failure	43	49.4
	Non-ergonomic mooring equipment design	35	40.2
	Equipment specification mismatch	29	33.3
	Inadequate maintenance	28	32.2
	Winch failure	19	21.8
Organizational Factors	Operational time pressure	49	56.3
	Safety procedures are inadequate	34	39.1
	Lack of supervision	32	36.8
	Weak safety culture	26	29.9
	Limited human resources	22	25.3
Environmental Factors	Bad weather conditions	33	37.9
	Low visibility	25	28.7
	Limited maneuvering space	21	24.1
	Strong sea currents	18	20.7
	Inadequate port infrastructure	15	17.2

Table 1 shows that communication errors (71.3%), fatigue (58.6%), and operational time pressure (56.3%) are the three most frequent risk factors contributing to mooring line accidents. In the technical factor category, rope material failure (49.4%) is the dominant factor, while bad weather conditions (37.9%) are the most influential environmental factors.

3.2 Analysis of Interaction of Human and Technical Factors in Mooring Rope Accidents

Based on correlation analysis and structural equation modeling (SEM), this study successfully identified patterns of interaction between human and technical factors in the chain of mooring rope accident events. Table 2 presents the correlation coefficients between the main risk factors that indicate the strength of the relationship between variables.

Table 2. Correlation Coefficients between Main Risk Factors (Pearson's r, n=341)

Risk Factors	1	2	3	4	5	6	7	8
Communication error	1.00							
Fatigue	0.67**	1.00						
Lack of training	0.58**	0.43**	1.00					
Rope material failure	0.31*	0.27*	0.35**	1.00				
Operational time pressure	0.62**	0.71**	0.39**	0.33**	1.00			
Inadequate maintenance	0.29*	0.25*	0.56**	0.64**	0.38**	1.00		
Bad weather conditions	0.23*	0.36**	0.19	0.44**	0.27*	0.30*	1.00	
Weak safety culture	0.47**	0.42**	0.69**	0.38**	0.54**	0.59**	0.21*	1.00

Note: * $p<0.05$, ** $p<0.01$

The results of the correlation analysis in Table 2 show a significant relationship between human and technical factors. There is a strong correlation between lack of training and inadequate maintenance ($r=0.56$, $p<0.01$), and between fatigue and operational time pressure ($r=0.71$, $p<0.01$).

Based on the results of the SEM analysis, an interaction model of human and technical factors was found that explained 68.7% of the variance in mooring rope accidents. Table 3 displays the results of the path analysis showing the direct and indirect effects between risk factors.

Table 3. Results of Path Analysis of the Interaction Model of Human Factors and Technical Factors

Path	Direct Effect	Indirect Effect	Total Effect
Time pressure → Fatigue → Communication errors	0.42**	0.31**	0.73**
Lack of training → Inadequate maintenance → Material failure	0.36**	0.29**	0.65**
Weak safety culture → Lack of training → Miscommunication	0.39**	0.27**	0.66**
Weak safety culture → Inadequate maintenance → Material failure	0.28**	0.32**	0.60**
Bad weather conditions → Material failure → Accident	0.24*	0.19*	0.43**
Communication errors → Unsafe positioning → Accidents	0.47**	0.25**	0.72**
Material failure → Accident	0.53**	-	0.53**
Communication error → Accident	0.58**	-	0.58**

Note: * $p<0.05$, ** $p<0.01$

Path analysis in Table 3 shows that operational time pressure has a strong total effect (0.73) on communication errors through the fatigue mechanism. In addition, weak safety culture contributes significantly to material failure (0.60) through inadequate maintenance.

Based on thematic analysis of qualitative data, there are five main interaction patterns between human factors and technical factors:

a. Operational Pressure Cascade: Operational time pressure → Fatigue → Communication errors → Accident
b. Competence-Equipment Degradation: Lack of training → Inadequate risk assessment → Inadequate maintenance → Material failure → Accident
c. Normalization of Deviation: Weak safety culture → Failure to follow procedures → Unsafe positioning → Accident
d. Environmental Condition Escalation: Adverse weather conditions → Additional stress on equipment → Personnel fatigue → Material failure → Accident
e. Crisis Communication Failure: Abnormal conditions detected → Communication errors → Delayed response → Accident

3.3 Safety Management System Evaluation

Based on document analysis and interviews with safety management personnel at four ports, this study evaluates the effectiveness of the implemented safety management system. Table 4 presents the results of the assessment of the safety management system components based on a scale of 1-5 (1: Very Inadequate, 5: Very Adequate).

Table 4. Evaluation of Safety Management System Components at Four Ports

SMS Components	Port A	Port B	Port C	Port D	Average
Mooring safety policy	4.2	3.8	3.5	2.7	3.6
Standard operating procedures	4.0	3.7	3.3	2.5	3.4
Personnel training program	3.7	3.5	2.9	2.2	3.1
Equipment inspection and maintenance system	3.5	3.2	2.8	2.3	3.0
Pre-operative risk assessment	3.3	3.0	2.5	2.0	2.7
Incident reporting system	4.3	3.9	3.4	2.8	3.6

Learning from the accident	3.6	3.1	2.7	2.1	2.9
System audit and review	3.2	2.9	2.3	1.9	2.6
Management involvement	3.8	3.4	2.6	2.2	3.0
Risk communication	3.4	3.1	2.5	2.0	2.8
Overall average	3.7	3.4	2.9	2.3	3.1

The evaluation results showed significant variation in the implementation of safety management systems between ports, with Port A showing the best performance (average 3.7) and Port D showing the lowest performance (average 2.3). In general, the safety policy and incident reporting system components had the highest ratings (3.6), while audit and system review had the lowest ratings (2.6). Correlation analysis between safety management system component scores and mooring line accident rates at each port (last three years) showed a significant negative relationship ($r=-0.78$, $p<0.01$), indicating that ports with better safety management systems tend to have lower accident rates.

4. Discussion

The results of the study indicate that mooring accidents in ship operations at the port are complex phenomena influenced by the interaction of various risk factors. The findings regarding the dominance of communication errors (71.3%), fatigue (58.6%), and operational time pressure (56.3%) as the main contributors to accidents confirm the importance of the human aspect in the chain of accident events. This is in line with previous studies in the field of maritime safety which often identify the human factor as a critical element in 70-80% of accidents in the port environment. Communication errors as the dominant factor indicate fundamental problems in the process of exchanging information during mooring operations, which can be in the form of miscommunication between ship crew and shore personnel, the use of non-standard terminology, or interference in the transmission of important information. Correlation analysis and structural equation modeling (SEM) revealed complex interactions between human and technical factors in accidents. The strong correlation between lack of training and inadequate maintenance ($r=0.56$) shows how deficiencies in personnel competence can impact the technical aspect of mooring operations. Likewise, the high correlation between fatigue and operational time pressure ($r=0.71$) emphasizes the impact of efficiency demands on workers' physical and mental conditions. The five main interaction patterns identified, particularly the "Operational Stress Cascade" and "Equipment-Competence Degradation," illustrate how risk factors interact and create conditions conducive to accidents. These results underscore the importance of a systems approach to understanding and preventing mooring line accidents, taking into account the interactions between humans, technology, organizations, and the environment.

The safety management system evaluation revealed significant variation across ports, with Port A performing the highest (mean 3.7) and Port D performing the lowest (mean 2.3). A significant negative correlation ($r=-0.78$) between safety management system scores and accident rates indicates the importance of implementing an effective safety management system in reducing the risk of accidents. Areas requiring particular attention are system audits and reviews (mean 2.6), pre-operational risk assessments (mean 2.7), and accident learning (mean 2.9). Low scores on these components indicate gaps in the proactive approach to safety management, with ports tending to focus more on policies and incident reporting than on continuous evaluation and learning processes. Strategic recommendations developed based on the research findings reflect a comprehensive approach to mitigating the risk of mooring line accidents. The high priority given to the development of standardized communication protocols (score 18.9) and the implementation of mandatory pre-operational briefings (score 18.0) confirm the importance of interventions on human factors, particularly communication and situational awareness. Meanwhile, the implementation of a sensor-based mooring rope condition monitoring system (score 15.0) shows the potential of the technology in improving the safety of mooring operations. Mitigation strategies that focus on high-priority interventions with good potential effectiveness and ease of implementation can be an efficient first step in reducing the risk of mooring rope accidents.

The findings of this study have important implications for maritime safety practices in Indonesian ports. First, there is a need for standardization of communication procedures and more comprehensive training for mooring personnel. Second, port management needs to develop strategies to reduce excessive operational time pressures, for example through better planning and adequate resource allocation. Third, the integration of human factors in the design of technical systems and operational procedures is essential to create a safer working environment. Fourth, a proactive approach to safety management, including pre-operational risk assessments and accident learning, needs to be strengthened in all ports. Fifth, national regulations related to mooring safety need to be reviewed and strengthened to create consistent minimum standards across Indonesian ports.

This research is in line with previous research [18] which highlights that maximizing deck space for cargo reduces the space available for mooring operations, especially on the aft deck, which forces operators to work in dangerous zones. The humancentered design approach can provide better solutions for mooring equipment design that considers the needs and safety of the crew.

5. Conclusion

The study successfully identified the main risk factors for mooring line accidents in port vessel operations, with communication failure, fatigue and operational time pressure being the three dominant factors, while factor interaction analysis revealed a complex pattern of relationships between human and technical factors contributing to the chain of events with five main interaction patterns identified; evaluation of safety management systems revealed significant variation across ports, with areas for improvement including pre-operational risk assessments, system audits and reviews, and accident learning; implementation of pilot interventions showed positive results with a significant reduction in incidents, indicating that an approach focused on the development of standardized communication protocols and mandatory pre-operational briefings could be an effective strategy for mitigating the risk of mooring line accidents in the short term, while in the long term, a combination of technical, operational, management and regulatory interventions are needed to comprehensively address the risk factors.

This study has several limitations that need to be considered, including the limited sample size in a few specific ports, which reduces the generalizability of the findings, bias in retrospective data collection that relies on incident reports that may not include near-misses or minor incidents, and the relatively short observation period of the pilot intervention implementation to evaluate long-term effectiveness; in addition, this study was unable to fully control for external variables such as extreme weather conditions or changes in port policies that may have affected the results of the intervention implementation. For future research, a more comprehensive longitudinal approach is planned with a wider sample of ports in terms of geography and operational characteristics, the development of a more integrated incident reporting system to minimize data bias, implementation and evaluation of the intervention over a longer period (at least two years) to assess the sustainability of effectiveness, and an in-depth analysis of aspects of port safety culture and how it affects compliance with mooring safety protocols, with a particular focus on the development of decision-making aid technologies that can integrate weather conditions, vessel characteristics, and human factors data.

Conflict of Interest

The authors declare no conflict of interest.

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