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Evaluation of ballast failures during operations of semi-submersible rigs

N Unegbu, and O T Gudmestad

Department of Mechanical and Structural Engineering and Materials Sciemce, University of Stavanger, Norway

Contact address of authors: Nneomaaguta@yahoo.com, ove.t.gudmestad@uis.no

Abstract. Risk analysis/assessment is one of the challenges encountered during operations of offshore units on the Norwegian Continental Shelf (NCS). In recent years, the Petroleum Safety Authority (PSA) has focused on hazards relating to floating installations and thus requested that more attention should be made by the industry on hazards relating to buoyancy loss and stability. Ballast systems play a very vital role to ensure vessel stability. Various failure modes of semi-submersible ballast systems are identified and possible barriers and consequences due to the ballast system failure during drilling operation are considered. The failure mode effect and criticality analysis (FMECA) of the main components of the semi-submersible's ballast system is adopted to determine the failure causes and failure modes that could influence each components performance, and thus identifying the most critical component(s). The Structured What-If Technique (SWIFT) is used to compensate for hazard identification for the unidentified hazards (i.e., human errors), in the FMECA. By studying the most critical system components, a qualitative risk analysis is conducted to model accidental sequences by using the fault tree method to establish the chain of failure events. The result of the Structured What If Analysis (SWIFT) shows that maloperation of the ballast system is the main contributing failure cause. This involves, failure to properly describe ballast procedure, failure to follow ballast plan, wrong sequence of closing/opening valve, maloperation of valve, time pressure complacency, communication gap or general lack of knowledge of the system. The FMECA findings indicate that failure of valves to "close on demand" with a Risk Priority Number (RPN) of 60, is the most critical.

1. Introduction

The Norwegian Petroleum Safety Authority, PSA has focused on hazards relating to floating installations in the past couple of years and requested that more attention should be made by the industry on hazards relating to buoyancy loss and stability [1, 2]. Ballast systems play a very vital role to ensure vessel stability. The main function of the ballast system is to maintain stability and sufficient draft, and also to retain the shear forces and bending moments within required limits. The ballast system comprises of; ballast tanks, different networks of pipes, pumps and valves, hydraulic power system, electric power system and ballast control system.

A failure can be disastrous in nature. It also has tendencies to lead to other unwanted consequences even if it is not catastrophic. For instance, it could cause production loss in the event of downtime and prolonging of delivery deadlines. This therefore, affects projects in the sense of additional costs and

wastage of resources hence, leading to the possibility of losing customer goodwill [3]. Failure to properly ballast may lead to accidents, which could potentially lead to loss of vessel, death of personnel and environmental disasters [4]. According to a research carried out by [5] on risk assessment of buoyancy loss (RABL), after vessel collision, the second main contributor to risk in terms of buoyancy loss and stability for offshore mobile drilling units is ballast system failure [6].

This paper aims to evaluate the failure of ballast systems' components during drilling operations. These evaluations include: consequence classification of the critical components of the ballast system; Identification of ways the systems, components, or processes fail to realise their design purpose; Identification and analysis and factors and conditions that cause to the occurrence of an undesirable event; Identification of safety barriers that aims to prevent; Control and mitigate effects of a hazardous event

2. Hazard identification

Hazard identification (HAZID) involves a thorough and comprehensive identification and documentation of hazards. It is very important to thoroughly carry out a comprehensive identification and recording of hazards because failure to identify any hazard at this stage might be detrimental, as it would not be considered in further assessment [1]. Therefore, a comprehensive and well-planned hazard identification is a critical basis for other elements in risk assessment.

2.1. Structured What-If technique

A structured What-If Technique (SWIFT) is a risk analysis method where a lead question "What if" is used to systematically identify potential deviations from normal conditions [7]. This technique is team-oriented and uses experienced personnel as team members. The hazard identification is based on brainstorming by utilising a generic checklist of elements to be reviewed. It is flexible for the use of any type of operations at any given lifecycle stage [8]. Although the SWIFT analysis is rarely used to identify hazards in the offshore oil and gas, it is used here to compensate for unidentified hazards in the FMECA (i.e., Human related errors). Table 1 presents the generic checklist and hazard brainstorming process hazard identification for the ballast system while Table 2 presents the Hazard identification based on SWIFT.

Table 1. Generic checklist and hazard brainstorming process of the ballast system.

Generic check lists	Hazard brainstorming
➢ Human factors (including operating errors)	1. Faulty ballast system design
➢ Maintenance	2. Vessel monitoring system failure
➢ Malfunction of equipment	3. Pump Failure
➢ Utility failure	4. Valve failure
➢ Measurement errors	5. Pipe failure
➢ Emergency operation	6. Remote System operation failure
➢ Integrity failure	7. Tank overpressure or under pressure
➢ External factors	8. Power failure
	9. Valve control system failure
	10. Maloperation of valves
	11. Poor maintenance
	12. Inadequate training
	13. Inadequate personnel selection process
	14. Tank over filling or under-filling
	15. Miscalculations

Table 2. Hazard identification based on SWIFT [8].

Ref.	Hazard Definition	Faulty ballast system design
1	Causes	Lack of regulation. Lack of experienced designer. Poor quality checking process. Financial constraints
2	Consequences	Failure to ballast efficiently. Low pump system capacity.
3	Safeguards	Approval process plan. Ballast tank capacity (Class/rules)
4	Recommendations	Design criteria must be considered.

Ref.	Hazard Definition	Ballast system failure
1	Causes	Failure or/and damage to pumps, pipes, valves etc. Suction Blockage. Insufficient/inefficient backup system.
2	Consequences	Inability to ballast. Inability regulate heeling. Unfavourable mass distribution.
3	Safeguards	Design. Maintenance. Limited redundancy
4	Recommendations	Adequate predictive maintenance strategy. Inspection. Performance testing and monitoring of ballast system

Ref.	Hazard Definition	Maloperation of ballast system
1	Causes	Failure to properly describe ballast procedure. Failure to follow ballast plan. Wrong sequence of closing/opening valve. Maloperation of valve. Time pressure. Complacency Communication gap. Lack of knowledge of the system
2	Consequences	Ballast system failure, Unfavourable heel or draft, unfavourable distribution of mass, Insufficient stability
3	Safeguards	Operating procedures. Monitoring. Training. Planning
4	Recommendations	Inclusion of performance monitoring in the ballast system procedures.

Ref	Hazard Definition	Inadequate planning of ballast operation
1	Causes	Lack of knowledge about the system. Missing description and training. Insufficient availability of personnel. Complacency. Failure to read accurate weather forecast.
2	Consequences	Ballast system failure, List, Structural damage, Loss of buoyance and stability
3	Safeguards	Training procedures, operational practice
4	Recommendations	Emphasis should be made on hazards regarding ballasting during training. Planning on competence availability of personnel

Ref	Hazard Definition	Loss of buoyancy/ insufficient stability
1	Causes	Flooding, structural failure, power failure, ballast system failure, large heel angle, loss of weather/water tight integrity. VCG movement and mass, free surface effects
2	Consequences	Failure of ballast system. Loss of platform. Power failure. Failure of ballast system to operate. Inability to launch live saving system.
3	Safeguards	Recognition of margins and regulations for stability
4	Recommendations	Emphasis should be made on hazards regarding ballasting during training. Planning on competence availability of personnel

Ref	Hazard Definition	Excessive heel during ballasting/ de-ballasting
1	Causes	Unfavourable mass distribution, Insufficient stability
2	Consequences	Failure of ballast system. Loss of platform. Power failure. Failure of ballast system to operate. Inability to launch live saving system.
3	Safeguards	Adequate design of ballast system
4	Recommendation	Design of ballast system should ensure adequate buoyance. Design miscalculations. Active response time with regards to effective intervention of the system

Ref	Hazard Definition	Loss of watertight integrity
1	Causes	Flooding through uncovered manhole, device with open and close functions
2	Consequences	Unwanted mass distribution. Ballast system failure. Insufficient stability. Total loss. Personnel injury/fatality
3	Safeguards	Operational procedures. Inspection
4	Recommendation	Procedures watertight integrity loss must be implemented

2.2. Failure Mode Effects and Criticality Analysis

A FMECA is carried out to reveal and analyse failure modes, failure causes and failure effects on the main components of the ballast system. This method systematically analyses all possible failure modes and its direct reflection on the system's performance [9]. The FMECA also enables predictions to be made on the failure effects on the system and how the failures could be avoided. This can be achieved by ranking the criticality of the failures. By knowing the critical components, improvements are made for reliability and safety purposes. A detailed description of the FMECA can be found in [9]. Table 3 presents a breakdown of the ballast system.

Table 3. Analysed components by FMECA technique.

Ballast tank configuration	
	Ballast tanks
Ballast control system	
	Ballast valves and pump room valves Sea chest valves and Discharge valves Ballast pumps and Ballast control logic unit
Pipes	
	Pipes
Electric power system	
	Main electric power generator Emergency backup generator UPS
Hydraulic power system	
	Main hydraulic power generator Hydraulic accumulator

It should, however, be noted that FMECAs are based on a single failure principle. Compliance with a single failure requirement is not sufficient to avoid incidents. This is in line with [10] concluding that FMECA analysis are not sufficient to identify and remove all relevant single failure modes. FMECA also considers only hazards arising from single-point failures and will normally fail to identify hazard caused by combinations of failures. Furthermore, the interactions between subsystems are not assessed in the FMECA when failure modes are reviewed separately in each subsystem. We will also refer to

[11] who indicates that FMECA, sea trials, and hardware-in-the loop testing, are insufficient and that the view on safety using these methods is too narrow. The safety constraints can be violated in other manners than component failures, as with human errors. It also assumes that failures are found and corrected before new errors occur. This is not in compliance with practice where errors are found, and put in a queue to be fixed together with other failures. After incidents, also other errors are typically found which were unknown before the incident. Still we suggest that FMECA is a method well suited initially to identify failures.

Functions of the elements in the ballast systems are considered together with their operational modes. For each of the functions and operational mode, possible failure modes are identified and listed. The failure modes are ranked according to their frequency of occurrence (O), severity (S), and the likelihood that the failure is detected on time (D). It is important to note that the failure modes were assigned subjectively based on sources including; RABL datasheet, OREDA reports, "Riskonivå i petroleumsvirksomheten" (RNNP) reports, reports on past incidents etc. The ranks are given ranging from 1 (lowest) to 5 (highest). The risk priority number (RPN) is therefore determined by multiplying the occurrence, severity and detectability. During the FMECA some assumptions were made. They include:

- It is assumed that one component fails at a time
- Human error contributions are neglected
- Failure modes analyzed are the more frequent failure modes but not the modes analyzed comprehensive
- The identified failure causes are not a full assessment of all the failure modes of the components

Based on the analysis, the components with the highest ranking are the valves, hence the most critical.

3. Risk reducing measure (barrier analysis)

As pointed out earlier, the oil and gas industry is faced with the risk of major accidents. Major accidents here mean accidents which has major consequences, capable of causing fatalities or/and environmental hazards. Fortunately, these unwanted accidents have low probability of occurrence due to presence of multiple layer of protection, otherwise known as barriers [12]. Although there may be possibility of a single failure to occur, it should not be allowed to lead to catastrophic events. Thus, the reason why multiple barriers are in place and need to be strategically managed all through the rigs' lifecycle [12].

Safety barriers are established and implemented with the aim of preventing, controlling and mitigating the effects of a hazardous event [13]. Depending on the scenario the ballast system is used as a safety barrier in order to prevent, control and mitigate unwanted lists of the vessel by means of ballasting. Barrier management is carried out, with the purpose of establishing and maintaining barriers to prevent unwanted event or in situations where unwanted events occurs, it can be properly handled [14]. Barrier management includes systems, processes solutions and measures that must be readily available to reduce risk by the implementation and follow–up of barriers [14].

3.1 Barrier analysis of past incidents/accidents

The event sequence is the basis of a barrier diagram. It is represented as rectangular text boxes that are linked. Adopted from [15], Figure 1 shows a sample and description of the barrier diagram used in this paper to provide an event sequence overview leading to the accident.

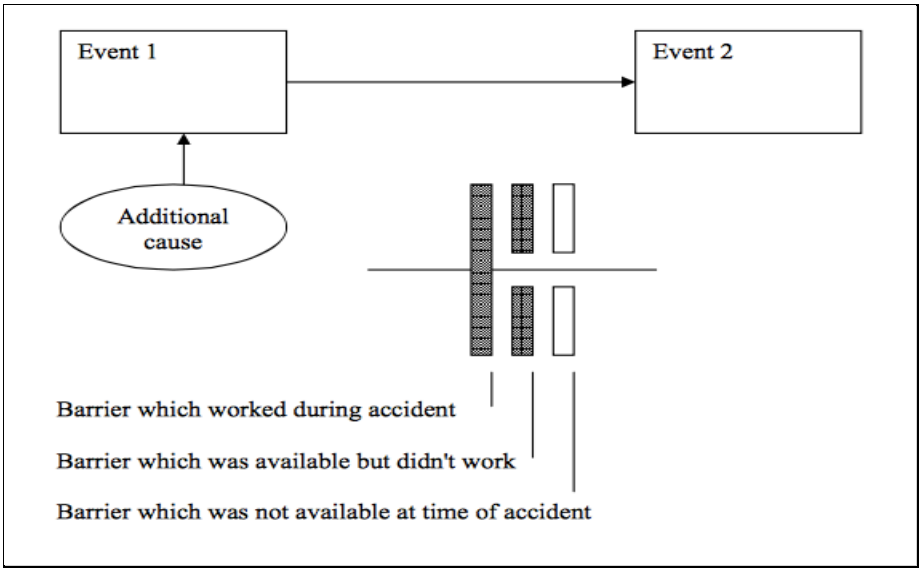

Figure 1: Barrier diagram

Additional causes are presented in the circular box. The shaded or white vertical bars represents the barriers. The shaded barriers mean the availability of barrier at the time of incident. White broken barriers represent barriers that were not available in the duration of time the incident occurred but were implemented in regulations. A full shaded barrier means that the barrier worked.

Reference [16] presents a detailed barrier analysis of accidents/incidents of nine selected rigs. An overview of the analyzed accidents for five of the rigs is shown in Table 4 and the barrier performance summary in Table 5.

Table 4. Overview of the analysed accidents.

Unit	Location	Year	Main cause
Ocean Ranger	Canada	1974	Ballast System, Portlight
Ocean Developer	West Africa	1995	Ballast system operation
Petrobras-36,	Brazil	2001	Operation of drainage, Hydrocarbon explosion, flooding
Thunder horse	Gulf of Mexico, US	2005	Hydraulic system operation
Scarabeo 8	Barents Sea, Norway	2012	Ballast system operation

Table 5. Barrier performance summary.

Barrier Function performance	Maintain Structural Integrity and Marine Control	Prevent escalation of initiating failure	Prevent loss	Prevent fatalities/ injuries
Ocean Ranger accident	Failure	Failure	Failure	Failure
Ocean Developer	Failure	Lack of Information	Lack of Information	Success
Petrobras-36 Accident	Failure	Failure	Failure	Partial Success
Thunder Horse	Failure	Success	Partial Success	N/A
Scarabeo 8 Incident	**Failure**	**Success**	**N/A**	**Partial Success**

The analysis shows the direct implications of barrier failures in terms of technical operational and organizational elements. In one way or other, human errors are significant as these are the main contributor to this failure. The initiating cause of failure for three of the incidents are directly linked to human involvement (i.e., Ocean Developer, Thunder Horse and Scarabeo 8). In the case of Ocean Ranger, the series of events that caused the accident was solely caused by poor design. The Petrobras P-36 series of events occurred as a combination of fires and explosions and a design that did not allow for operating the ballast system following the damages in the column.

4. Discussion

A considerably amount of information about past events is needed to prevent near misses and accidents in the future. However, some loss of stability incidents and accidents are not reported, or we lack full information about the events leading to the accidents. The downside to this problem is that detailed studies are not carried out to know how and why the event happened, especially for peculiar cases. This may be the reason why damage frequency on vessels have not improved over the years. Figure 2 presents a distribution of causes of nine selected past incidents/accidents that led to loss of buoyancy or loss of stability of semi- submersibles. Five of these are listed in Tables 4 and 5 while four additional cases were studied in [16]: Henrik Ibsen, Abel Peal, Flotel Superior and Island Innovator.

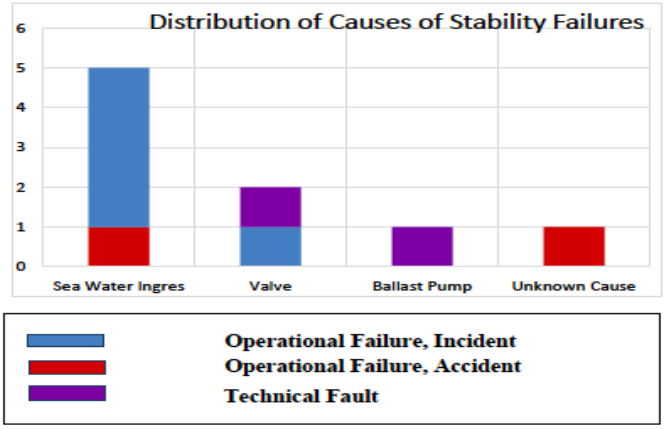

Figure 2. Distribution of causes of nine selected past incidents/accidents that led to loss of buoyancy or loss of stability of semi- submersibles.

A more detailed information about some semi-submersibles and their dimensions are given in the following. Five out of the nine incidents/accidents, were caused by uncontrolled water ingress. This is in line with the conclusion by [17], who noted that uncontrolled water ingress is the main common cause of accidents and incidents. On the other hand, a similar study carried out by [18] concluded that valve failures are the main cause category for incidents and accidents. This discrepancy may be due to the fact that in most cases where ballast valve failure is not the initiating cause of an event, however it seen to be among the casual factors on the incident chain. It is further observed that seven out of nine incidents/accidents occurred due to human errors. These accidents could have been prevented if the human interface (i.e., designers, operators and organization) had followed the guidelines in [19], PSA (2011) regulations. Therefore, when carrying out hazard analysis on systems such as this, it is important to incorporate human errors.

Risk assessment on ballast systems can be done by adopting either the qualitative approach, quantitative approach or a combination of both. However, this paper is limited to qualitative risk assessment of ballast failures during operations of semi-submersibles. The first step of this assessment method is aimed at identifying potential hazards that could be detrimental to operations. The techniques adopted are the SWIFT and FMECA.

The FMECA was adopted to systematically analyze all possible failure modes and their direct

reflection on the performance of the ballast system. The SWIFT method was used to compensate for unidentified hazards in the FMECA (i.e., human related errors). The hazard identification is based on brainstorming by utilizing a generic checklist of elements in the ballast system. Table 2 shows a comprehensive hazard identification based on SWIFT. Hazards here are defined are follows;

- Faulty ballast system design
- Failure of ballast system
- Maloperation of ballast system
- Inadequate planning of ballast operation
- Loss of buoyancy /inefficient stability
- Excessive heel during ballasting /de-ballasting
- Loss of watertight integrity or weather-tight integrity

The causes and consequences for each of the defined hazard are identified. For instance, maloperation of the ballast system can occur due to failure to properly describe ballast procedure, failure to follow ballast plan, wrong sequence of closing/opening valve, maloperation of valve, time pressure complacency, communication gap or general lack of knowledge of the system. Controls otherwise known as safeguards are also identified as a risk-reducing measure. Finally, recommendations are made on how to achieve the safeguard (also see Table 2 for recommendations).

A FMECA was carried out to reveal and analyze failure modes, failure causes and failure effects on the main components of the ballast system. Information about the failure rates were acquired from the RABL data sheet, OREDA report and the RNNP report. The risk relating to the failure modes are presented by an alternative to the risk matrix, (i.e., Risk priority number (RPN). The RPN is determined by multiplying together the severity (S), occurrence (O) and detectability (D) of the failure modes. Numbers are subjectively assigned to the S, O, D based on the authors' degree of knowledge of the components. A detailed FMECA is presented by [16]. The findings show that failure of valves to "close on demand" is most critical.

It is established that the risk related to ballast failure can lead to fatalities or/and loss of platform. In order to prevent or reduce the consequences in the event the incident occurs, a risk reducing measure must be in place. The risk reducing measure adopted in this paper is barrier management. A detailed barrier analysis of five selected rigs accidents/incidents showed the direct implications of barrier failures in terms of technical operational and organizational elements. Human error was established to be the main contributor to this failure. The initiating cause of failure for three of the incidents are directly linked to human involvement (i.e., Ocean Developer, Thunder Horse and Scarabeo 8). In the case of Ocean Ranger, the series of events that caused the accident was caused by poor design. The Petrobras P-36 series of events occurred as a combination of fires and explosions and a design that did not allow for operating the ballast system following the damages in the column. In order to ensure that barriers are functioning, robust and available, it is important to have a defined barrier management strategy.

Figure 3 establishes an approach of barrier risk reduction. This approach starts with hazard identification of critical paths of the ballast system that may lead to a major accident. The second step aims to apply solutions that involve technical, operational or organizational aspects. This could be in the form of design modifications, improvement or changes in procedures and personnel selection process (i.e., to increase competence in ballast operations). A detection (e.g., sensors) and ballast control safety barriers must be available in order to detect events with critical deviations. In addition, mitigation barriers (i.e., reserve buoyancy in the form of buoyancy deck, air injection etc.) to prevent total loss should be established. Finally, performance monitoring must be an ongoing process. This will aim to continuously monitor the performance of components in the ballast system with the human interface.

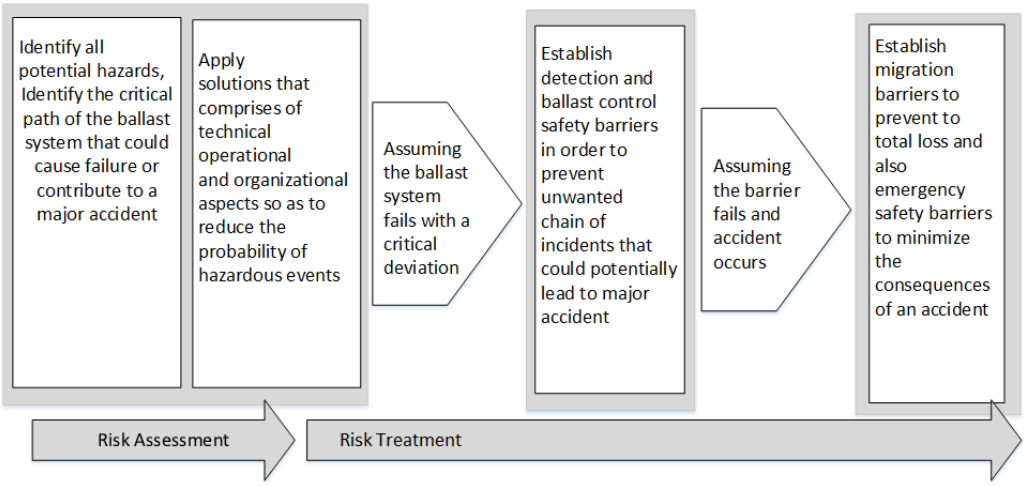

Figure 3. Barrier risk reduction.

5. Conclusions and future works

The consequences of instability of semi-submersible rigs during operations are considered to be severe. Hence, this paper is focused on integrating operational stability calculations of a semi-submersible rigs with risk analysis. The purpose of is to evaluate the failure modes of ballast system's components during drilling operation and suggest mitigation measures. To achieve this objective a qualitative risk assessment approach is adopted.

Some past incidents and accidents were reviewed in order to identify and understand causes and chains of accidental events. The reviewed literature included investigation reports on, Ocean Ranger, Ocean Developer, Petrobras P-36, Thunder Horse and Scarabeo 8. Also reports on accidental situations with the semisubmersibles Henrik Ibsen, Abel Peal, Flotel Superior and Island Innovator were considered in [16], however, not discussed in this paper.

Critical events were identified in the FMECA relating to changes in the amount of ballast water. Also, components in the ballast system were analyzed, and based on findings, the failures of valves to *"close on demand"* with a Risk Priority Number (RPN) of 60 was established to be the most critical. It is important to note that the valves regarded here are the valves in the ballast tank configuration. The SWIFT analysis identified human operational hazards that was not identified in the FMECA. A fault tree was then used to represent the relationship between events and component failures that may combine to cause an un-desirable event. Finally, it was established that, in order to ensure that barriers are functioning, robust and available, it is important to have a defined barrier management strategy.

As a future work, the study efforts and other past studies related to risk analysis of the ballast system of a semi-submersible during operations have identified fundamental information about reliability and risk analysis of the ballast system of a semi-submersible. However, further studies are required to improve the accuracy of the results of the study efforts and to reveal more efficient methodology for reliability and risk analysis. Therefore, future studies that might be considered are not limited to the following:

- Detailed quantitative risk and reliability analysis of potential ballast failures during operations of a semi-submersible
- Investigations that include integration of operational stability calculations of a semi-submersible rig with risk analysis. This thesis can serve as a foundation to such investigations
- Although this paper is limited to barrier management for risk reduction, it is recommended to integrate the risk acceptance criteria and ALARP principle so as to balance cost and safety of a selected risk reducing measure or strategy.

For more detailed analysis, quantitative risk analysis should be implemented in order to obtain a more accurate assessment of risks, the QRA would allow to implement assessment of single human errors, competence requirements, requirements to investigations and schemes for certification of the ballast systems etc.

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