University of
Stavanger

Faculty of Science and Technology

MASTER'S THESIS

Study program/Specialization: Risk Management	Spring semester, 2017
Writer: Ihuaku Nneoma Kelechi Unegbu	………………………………………… (Writer's signature)
Faculty supervisor: Prof. Ove Tobias Gudmestad (University of Stavanger, Stavanger Norway)	
Thesis title: Evaluation of Ballast Failures during operations of Semi-submersible rigs	
Credits (ECTS): 30	
Key words: Ballast failures, buoyancy loss, stability	Pages: 115 + Appendix /enclosure: Stavanger,June /2017

ABSTRACT

Offshore drilling is an operation performed to explore for and extract hydrocarbon beneath the seabed. The drilling operation is a very sensitive and extremely risky task and can be carried out from a floating vessel, semi-submersible and so on. Because of the high risk involved in drilling operations, the structural integrity and stability of the platform on which the drilling operation is performed are of uttermost importance to the success of the operation. In recent times, drilling operations are performed on mobile platforms most especially on semi-submersibles, thus the stability of this platform as well as the risk involved are worth given careful considerations and evaluations.

In the past couple of years, the 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. The main function of the ballast system is to maintain stability and sufficient draft, and also to retain the sheer forces and bending moments within required limits. The ballast system comprises ballast tanks, different network of pipes, pumps and valve, hydraulic power system, electric power system and ballast control system. Failure to properly ballast may lead to accidents which could lead to loss of vessel, death of personnel and environmental disasters as in the case of Ocean Ranger accident in 1982, and Petrobras P-34 FPSO in 2002 (Sobena, 2007).

This thesis is aimed at evaluating the risks involved in ballast operations, by identifying the various failure modes of semi-submersible ballast systems and we will consider possible barriers and consequences due to the ballast system failure during drilling operation. The thesis focuses primarily on the failure mode effect and criticality analysis (FMECA) of the main components of the semi-submersible's ballast system by determining the failure causes and failure modes that could influence each components performance, and thus identifying the most critical component(s). Also 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.

In addition to this, a stability analysis of a typical semi-submersible based on ballast system is performed to assess the criticality of different ballast failure conditions such as damage condition, and ballast failure under different environmental conditions such as under harsh environment, polar low occurrence. In achieving these objectives, both qualitative risk analysis and evaluation methods are adopted.

ACKNOWLEDGEMENTS

I would like to express my sincere appreciation to my supervisor, Prof. Ove Tobias Gudmestad, whose knowledge guidance and encouragement made every time I spent on this thesis extremely meaningful.
I am exceedingly grateful for the contributions of my classmate and colleague, Akinyemi Akinsanya for making this thesis a success. To Adekunle Orimolade for your helpful contributions and unwavering support in the execution of this work.

I would like to thank my family for their unconditional love and support. To my forever proud late parents Prof and Mrs R.M Aguta, thank you for molding me to be the lady I am today. To my brothers and sister, thank you for always being a call away irrespective of your schedules. Finally, to my daughter and husband, Zinachika and Tobenna, for your motivation and sacrifices

Ihuaku Nneoma Kelechi Unegbu
Stavanger, June 15, 2017

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ABBREVIATIONS

ALARP	As Low as Reasonably Practicable
BOP	Blowout Preventer
BP	British Petroleum
DFU	Defined Hazard and accident conditions
DNV	Det Norske Veritas
EDT	Emergency Drain Tank
ETA	Event Tree Analysis
FMEA	Failure Mode and Effect Analysis
FMECA	Failure Mode Effect and Criticality Analysis
FPSO	Floating Production Storage and Offloading
FTA	Failure Tree Analysis
HAZID	Hazard Identification
HSE	Health Safety and Environment
HMI	Human Machine Interfernce
MCT	Multiple Cable Transits
MODU	Mobil Offshore Drilling Unit
NMA	Norwegian Maritime Authority
ODECO	Ocean Drilling Exploration Company
OREDA	Offshore Reliability Data
OTC	Offshore Technology Conference
PDQ	Production and Drilling facility with Quarters
PSA	Petroleum Safety Authority
QRA	Quantitative Risk Assessment
RABL	Risk Assessment of Buoyancy Loss
RIF	Risk Influencing Factor
RNNP	Annual Trends in risk level report
RPN	Risk Priority Number
SINTEF	Stiftelsen for Industriel og Teknisk Forskning, Trondh
SIS	Safety Instrumented System
SNAME	Society of Naval Architecture and Marine Engineers
SWIFT	Structured What-If Technique
UPS	Uninterrupted Power Supply Database
VGC	Versatile Gas Component

1. INTRODUCTION

This chapter is aimed to introduce the background and objective of this thesis. This will include information on types of ballast failures, scope of work and also a description of the organization of the report.

1.1 BACKGROUND

Offshore drilling is an operation performed to explore and extract hydrocarbon from beneath the seabed. Recently the construction of offshore rigs is subject to advance in deep waters hence, safety is a major concern in the area of offshore field development. Accidents have occurred in the past, leading to loss of properties, human lives and also in some cases, ocean pollution (Vinnem, 2013). Due to the high risk involved in drilling operations, the structural integrity and stability of the platform on which the drilling operation is performed are of uttermost importance to the success of the operation.

In recent times, drilling operations are performed on mobile platforms, most especially on semi-submersibles. Therefore, the stability of this type of platform with the accompanying risk involved are worth given careful considerations and evaluations. Semi-submersible rigs are regarded as the most versatile drilling platforms in the marine industry (HSE, 2006). This is because they can be used for both deep (i.e., water too deep for fixed platforms) and shallow water. The semi-submersible is also preferred because of its, large riser holding space, good seakeeping capability, large topside space and easy offshore installation (Park et al., 2015). The first semi-submersible rig was developed in 1961 by the Blue Water Drilling Company. The unit had four columns and was used by Shell for drilling in the Gulf of Mexico. In 1971, it became rapidly accepted by the oil and gas industry after the construction of the first self-propelled semi-submersible by ODECO (Ismail et al., 2014).

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 (Vinnem, 2013). 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 sheer forces and bending moments within required limits. The ballast system comprises of; ballast tanks, different network of pipes, pumps and valve, 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 (Kumar *et al.*, 2007). Failure to properly ballast may lead to accidents, which could potentially lead to loss of vessel, death of personnel and environmental disasters (Sobena, 2007). According to a research carried out by Østby et al., (1987) 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 (HSE, 2003)

A typical initiating event due to ballast and equipment failure include: inadvertent flooding (e.g., Aban Pearl, Ocean Alliance, Diamond M Epoch and other incidents); human error during operation of the ballast control (e.g., Ocean Ranger, Scarabeo 8, Island Innovator, Ocean Developer, Petrobras P-36, etc.) (HSE, 2006).

Notwithstanding the potential of recognizing ballast failure related accidents, as a major accident, they are still not subjected to strict regulations by the maritime authorities. However, this may change because the regulation initiatives have included ballast systems under the performance-based section of the offshore regulations (OLF070, 2004).

1.2 PROBLEM DEFINITION

In the past, there has been a lot of incidents related to ballast failures. Based on major worldwide incidents and accidents discussed by Vinnem et al., 2006a, notable causes of ballast failures include; Ballast water pump, valve, firewater ingress and seawater ingress. It has been observed that valve failures are the major cause category for incidents and accidents. It is also observed that about 58% of all recorded incidents, accidents and minor problems are related to technical issues of which human error is usually the common cause

As drilling operation is a critical activity in the marine business, it is therefore very important to evaluate ballast failures during operation of semi-submersibles.

1.3 OBJECTIVES

The purpose of this thesis is therefore to evaluate the failure of ballast system's components during drilling operation. These evaluations include: Identification of the most 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

1.4 SCOPE

In order to achieve the objectives mentioned above, the following scope is covered:

1. Conduct a literature survey on similar models used in relation to the problem statement so as to determine the present research limit.
2. Conduct a failure mode effect and criticality analysis (FMECA) of the main components of the semi-submersible's ballast system
3. Model accident sequences by using fault tree to establish the failure frequencies of issues not corrected and/or caused by ballasting
4. Determine the barrier functions, barrier system and elements and risk influencing factors of past incidents
5. Use a case study to show the effects of ballast systems failure on semi-submersibles stability
6. Suggest risk reduction measures

1.5 ORGANISATION OF THE THESIS

Evaluations have been made on the most effective structure for introducing and analysing this thesis. This structure aims to allow the reader understand the purpose for the research. Therefore, the structure is divided into the following sections:

- **Chapter 1:** Provides the background and objective of this thesis

- **Chapter 2:** Presents an overview of this thesis

- **Chapter 3:** Presents the methodology used in writing this thesis

- **Chapter 4:** Discusses some past incidents on ballast system failure

- **Chapter 5:** Presents stability calculations of semi-submersibles

- **Chapter 6:** Establishes a risk assessment approach for identifying, analysing and mitigating ballast failures of semi-sumbersibles

- **Chapter 7:** Evaluates ballast failure of semi-submersibles

- **Chapter 8:** Concludes this thesis, and suggests recommendations for further research.

2. LITERATURE SURVEY

There has been an increase in demand of floating type offshore units, as a result of oil and gas exploration in deep seas. The semi-submersible type unit is widely preferred due to its, large riser holding space, good seakeeping capability, large topside space and easy offshore installation (Park et al., 2015). Presently, there has been very little research within the field of ballast systems during operations of semi-submersibles.

This chapter is divided into four sections. Section 2.1 describes the developments of the semi-submersible, section 2.2 presents an overview of the semi-submersible. Section 2.3 discusses past risk assessments that has been carried out in the field of ballast failure of semi-submersibles during operations. Section 2.4 discusses regulation requirements relating to vulnerability and reliability analysis and risk related to loss of buoyancy and stability

2.1 DEVELOPMENTS OF THE SEMI-SUBMERSIBLE

The evolution of semi-submersibles originated from the submersibles, which operated in relative shallow waters (Chakrabarti, 2005). The submersibles provided a deck above the highest projected wave. The rig transited between locations afloat on pontoons, requiring "*stability columns to safely submerge to a bottom founded mode of operation*" (Chakrabarti, 2005). Blue Water Drilling and Shell decided that the submersibles could operate in deeper water and developed the marine riser and refurbished the moorings, which allowed drilling in floating mode. This accidentally brought about the first semi-submersible, "*Bluewater*"

A significant progression on the development of semi-submersible rigs have been documented. John Filson in Chakrabarti, (2005 p.464), extensively researched on rigs from the 1st to the 4th generations. In addition, documentations from 5th and 6th generations can be seen in Kaiser et al., (2013). Generally, classifications of semi-submersibles into generations are based on the construction year, technology of equipment, variable deck load, environmental specification and water depth capacity (Kaiser et al., 2013). Table 2.1 lists the generations and characteristics of the semi-submersible platforms.

Table 2-1: Generation of semi-submersibles. *Source:* Chakrabarti, (2005), Kaiser et al., (2013)

Generation	Year of construction	Water depth [m]	Drilling depth [m]	Displacement [mT]	Variable load [tons]
1st	1962-1969	180 - 250	< 10 000	7 000-10 000	1 000 - 1 200
2nd	1971-1980	300 - 450	16 000 - 24 000	17 000 - 25 000	2 300 - 3 300
3rd	1981 -1984	460 - 770	25 000 - 30 000	25 000 - 30 000	3 800 - 4 500
4th	1984 -1998	1070 - 2200	30 000 - 53 000	30 000 - 40 000	3 800 - 5 000
5th	1999 -2005	2290 -3050	35 000 - 53 000	35 000 - 40 000	5 000 - 8 000
6th	2006 -	3050 - 3600	40 000 - 60 000	45 000 - 55 000	7 000 - 8 500

First Generation rigs (1960's)

According to Chakrabarti, (2005) semi-submersibles consists of a wide variety of configurations. They were developed all through the 1960s and were limited to water depths less than 250 metres. (Kaiser et al., 2013). The first rig of this kind (Bluewater 1) was used in 1961 by Shell Oil Company. Notable designs include the SEDCO 135 designs and the ODECO designs. The first generation submersibles became non-competitive as a result of lack of technology exchange of its designs, and lack of understanding of the vital principles of its designs (Chakrabarti, 2005). An example of this type of semi-submersible can be seen in Appendix A-1.

Second Generation (1971-1980)

The second-generation semi-submersibles have more technology exchange than the first (i.e., better mooring and subsea equipment). As drill ships became a major competitor, designers sorted out ways to make the semi-submersible more attractive. A major characteristic of the second-generation rig is the twin pontoon configuration, which enhances mobility (Chakrabarti, 2005). It was built for deep water up to 450m depth. Popular designs of the second-generation rig include; SEDCO 700, Aker H-3.0 and Friede and Goldman Pacesetter class (Kaiser et al., 2013). A typical example of this rig generation is the Essar Wildcat, Aker H-3.0 rig shown in figure A-2.

Third Generation (1981 -1984)

The third generation semi-submersibles was developed in the early 1980s. The platform operates on waters up to 770 m deep. There was a major paradigm shift in the design of semi-submersibles because of the Alexander Kielland and Ocean Ranger accidents (Chakrabarti, 2005). Emphasis were made on higher standards of structural redundancy and payload. Generally, the main characteristics of the third generation semi-submersibles include: increase in rig size, use of hull type structure, twin pontoon form continuation, and properly designed brace connection. An example of this generation rig is the Ocean Patriot, built in 1983 (See figure A-3)

Fourth Generation (1984 -1998)

There were few fourth generation semi-submersibles built in this period. This was because of the reduced demand for drilling driven by very low price in oil (Kaiser et al., 2013). Notable designs include; the GVA 4500s, Zane Barnes and the Henry Goodrich. The fourth generation rigs are able to operate in harsh environmental conditions and waters up to 2200m. Its main characteristics are the elimination of bracings and reliance of its hull-type superstructure. With the elimination of the bracings, accompanying problems that comes with bracings were also eliminated. This include; fatigue potential and maintenance problems (Chakrabarti, 2005).

Fifth Generation (1999 -2005)

The fifth generation semi-submersibles were constructed because of the demand of deeper water explorations. Although, its displacement is approximately the same as the fourth generation rigs there are some significant improvements on the unit's capability to go into deeper water and drill deeper as shown in table 1. This is due to its dynamic positioning (Kaiser et al., 2013). Significant performance was achieved as the drill floor systems, vessel management, power management, BOP controls and dynamic positioning, are not only integrated but also computer controlled. Fifth generation units typically have redundant dynamic positioning, automated pipe handling and powerful mud systems (Kaiser et al., 2013). An example of this generation rig is the Leiv Eiriksson (See figure A-5)

Sixth Generation (2006)

Rigs of this generation are rigs developed after 2005. As oil prices increased, demands to explore in new locations and also drill in deeper wells increased (Kaiser et al., 2013). The sixth generation have the capacity to operate in deep waters of more than 3000m. The rigs are also capable of operating in harsh environments including the Barents Sea, North Atlantic and calmer areas (e.g., West Africa) (Haug et al., 2009). The rig is winterized with heat tracing and cladded derrick in its base and can operate in warmer climate by means of chilled water units and an air-conditioned system. A typical example is the Transocean Spitsbergen, Aker H-6e design as shown in figure A-6.

2.2 DESCRIPTION OF THE SEMI-SUBMERSIBLE RIG

As stated earlier, there has been an increase in demand for floating type offshore units, as a result of oil and gas exploration in deep seas. The semi-submersible type unit is widely preferred because of its, large riser holding space, good seakeeping capability, large topside space and easy offshore installation (Park et al., 2015)

Figure 2-1: A semi-submersible rig. *Source*: ABB, n.d

Figure 2-1 presents a semi-submersible rig consisting of several systems. The topside is situated above the columns and is made up of living quarters, drilling derrick, drilling deck and operation equipment. The columns are usually made up of four or eight legs. These columns support the top side and provides adequate air gap between the deck and the water. Also, the columns are used for ballasting, as well as store bulk loads including fuel and drilling mud. The number of legs the column has is dependent on the required variable deck load capacity and stability. The units are usually designed with either a ring pontoon or two pontoons, which connects the columns. The pontoon provides the rig with the required buoyancy (Sharma et al., 2010). The hull is used for storing fuel, mud and ballast water. A brace is usually used to fortify the columns and pontoons to enhance the unit’s structural integrity.

Generally, when designing the semi-submersible rig, the following must considered. This includes (Chakrabarti, 2005);

- Intact and damage stability
- Weights and central of gravities
- Tank capacities
- Current Forces
- Wind Forces (i.e., mooring and stability loads)

- Performance of Ballast system
- Motions (i.e., drift and low frequency mooring loads)
- Fatigue
- Global Strength

It is also important to note that three configurations must be considered when designing the draft. These include; the operational, survival and transit draft. The draft is at the maximum magnitude during operation. This ensures that the pontoons are subjected to low pressure variation, hence favorable motions required during operations is achieved. In the case of extreme weather, the rig will stop operation and deballast. This will increase the air gap from the water surface to the rig thereby, preventing the waves from slamming into the deck. In addition, the water plane area will provide the rig with the necessary stability during transit.

Generally, for floating production installations and mobile units, stability loss is caused either by a single failure or by a combination of different causes. Vinnem, (2013) listed some of these causes, they include;

- Operational failure of ballast systems.
- Failure of ballast system components, including valves and pumps
- Human error by filling of buoyance volumes, water filling of volumes on the deck or maloperation of internal water sources, including fire water and water tanks
- Filling of buoyancy volumes due to the ingress of water caused by collision impact
- Filling of buoyancy volumes due to errors in design or construction
- Large weight displacement on deck
- Loss of weights as a result of anchor line failure or failures in the anchor line brake

2.3 RISK ASSESSMENT

2.3.1 Previous studies of ballast system failure

Generally, the ballast system is essential in performing tasks relating to operability and survivability of a rig. The design of the ballast system commenced with just a few pumps, few tanks and a simple manifold system (Sname, 1989). The deeper semi-submersibles were used in offshore operations, the more complex its system became. This meant that the platforms required additional buoyancy to be able to take more variable loads and moorings and different geometries for improved motion characteristics (Sname, 1989). Therefore, there was a downsize of compartmentation so as to meet the criteria for damage stability. The amount of ballast pumps stayed the same, which increased the complexity of the manifolds.

Very little research has been carried out within Risk assessments of Buoyancy loss (RABL). The RABL programme was initiated as a collaborative industry project, with the purpose of developing a procedure to define and analyse accidental conditions relating to loss of buoyancy for mobile drilling rigs (HSE, 2003). One of the projects that were looked into involved ballast systems. Following the capsize of the semi-submersible rig, Ocean Ranger in 1982, Østby et al, (1987) carried out an RABL research. It was primarily based on raising awareness on the assessment of the reliability of ballast system on mobile rigs. The programme involved the development of an approach for analysing ballast system failures by using fault trees and event trees. The project also supported the use of failure mode and effect analysis (FMEA) in the event where hazards are identified (HSE, 2003). Generally, the RABL methodology was overall considered to be sensitive and robust. It was recommended to be used in the assessment of safety levels when designing new platforms or already built platforms subject to changes during operations (HSE, 2003)

Problems associated with risk assessment of buoyancy loss for semi-submersibles was brought further into limelight following the accident of the P-36 semi-submersible platform on the Roncador Field in 2001. This led to the establishment of the Excellency Operational Program by the Brazilian oil company, Petrobras (Rocha et al., 2010). The objective of the program is to establish series of tasks aimed to improve operational reliability and safety of its rigs (Rocha et al., 2010). This resulted to a qualitative risk assessment approach for reliability and risk analysis of the interaction between components of the ballast systems (i.e., hydraulic and electric power systems, ballast system, and control systems) on the platform. In 2005, the methodology became compulsory for new floating platform projects. Rocha et al. (2010) performed a quantitative reliability study based on the qualitative studies (i.e., fault tree analysis and FMECA). They recommended that the control system, which has components with the least reliability, should be subjected to safety integrity level analysis as seen in IEC 61511 standard (norskeoljeoggass, 2004).

Nilsen (2005), surveyed on the recent Quantitative Risk Assessment (QRA) studies in the Norwegian continental shelf relating to stability of floating production and mobile units. He concluded that, the recent studies are unsuitable to identify possible risk reducing measures and are not suitable to quantify how such measures affects the risk levels. Other deficiencies in the QRA studies include (Vinnem, 2013): Lack of modelling of accident scenarios; Some failure mechanisms such as operator error during ballasting, are not considered; As opposed to PSA regulations, assumptions simplifications and premises are not addressed; and presentation results are usually not traceable hence worthless in terms of transparency. This is so because it fails to completely document the underlying assumptions and limitations.

Lotsberg et al., (2004) adopted an alternative to approach the QRA. This approach presented in figure 2-2 was used in the Kristin field. Comparing to the traditional QRA approaches, this approach is somewhat of an improvement (Vinnem, 2013). It involves using historical data to establish probability of failure of platforms, establishing risk influencing parameters and calculating a weighted grade on the operating parameters of the platform. However, the drawback of this approach is its inability to identify risk reducing measures and the associating risk of the risk reducing measures (Vinnem, 2013).

Vinnem et al., (2006) proposed an analytical approach as an alternative to the traditional QRA adapted from Haugen (2005). This approach was aimed to make up for the lapses in the both the traditional QRA methodologies and the failure frequency assessment approach. The studies addressed possible occurrence of some conditions during, for example, inspection and maintenance when opening manholes or when systems are deactivated (Vinnem, 2013). Figure 2-3 presents an analytical schematic of this approach. The analysis starts with collection of experience data and is followed up with hazard identification (HAZID). Hazard identification is carried out to identify scenarios that have the tendency

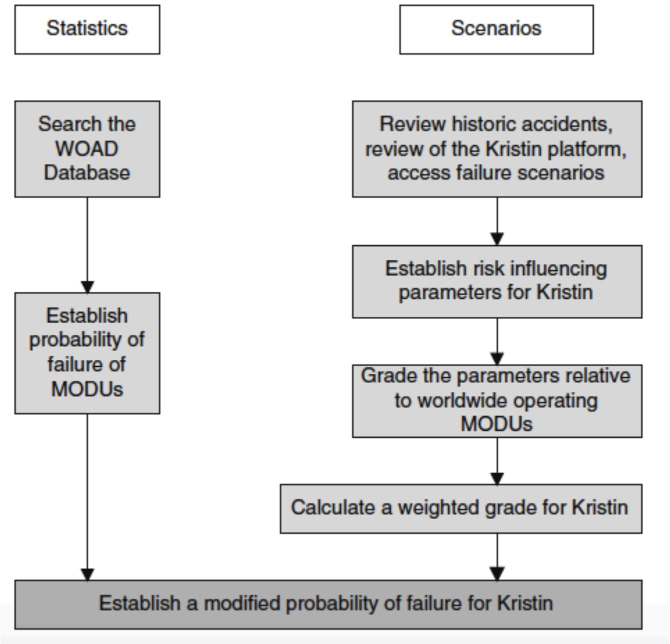


Figure 2-2: Failurefrequency assessment approach based on gross errors. Source; Lotsberg et al. (2004); Vinnem (2013)

to lead to critical consequences with respect to failures and effects of operational error (Vinnem, 2013). After the hazard identification process is established, a detailed analysis is carried out. The starting point of the detailed analysis could involve a Failure Mode effect and Critical Analysis (FMECA), fault trees and event trees. In the case of ballast related issues, Vinnem, (2013) suggested that a detailed analysis should involve critical scenarios limited to or influenced by marine systems.

Another important reason the analytical approach is recommended is because it reduces risk level by providing detailed information on the identification of the system modification and operational changes (Vinnem, 2013). This is a vital requirement in the management regulations (PSA, 2011b). Risk reducing measures is also an important step in the ALARP (As Low as Reasonably Practicable) process, which is used in the UK and Norwegian regulation. The ALARP principle states that “a risk reducing measure must be implemented; unless it can be shown that the cost is grossly disproportionate to the benefits” (Aven, 2008). Vinnem, (2013) concluded that, in addition to the described RABL approach, the following approach should be implemented;

- Fault tree analysis should be performed for the most critical nodes in the event tree
- Fault tree analysis should contain human and organizational errors where relevant
- Common mode failures and dependencies should be included in the fault tree analysis

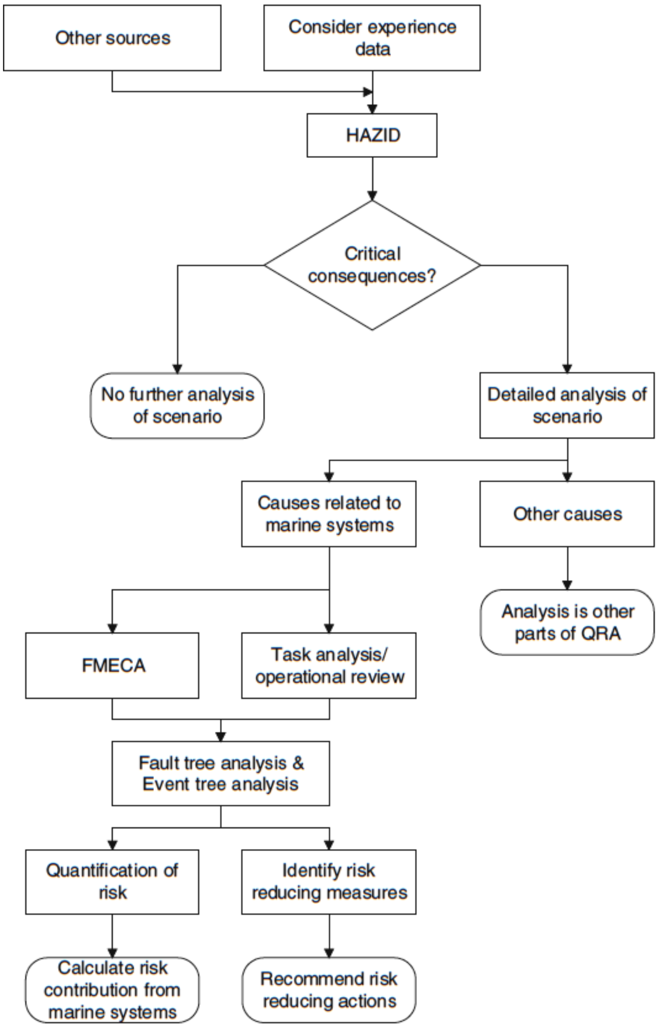


Figure 2-3: Analytical process for marine systems. *Source;* Vinnem (2013)

2.4 REGULATIONS

Regulatory requirements discussed in this section are requirements relating to vulnerability and reliability analysis and also risk related to loss of buoyancy and stability. Standards and requirements are available for design of floating units and ballast systems. The requirements for risk analysis of these systems is not straightforward (Vinnem, 2013).

Stability of floating facilities and ballast systems are regulated in two ways, the Norwegian Maritime Authority (NMA) and the Petroleum Safety Authority (PSA). NMA is a Norwegian government agency whose main job is to ensure that Norwegian shipping companies and ships meet required safety and required standards (Sjøfartsdirektoratet, n.d). The NMA also ensures that personnel have required qualifications and also work and live in good conditions. The NMA works hand in hand with the PSA to assist on issues concerning petroleum activities (PSA, 2011b). Petroleum Safety Authority (PSA) is the regulatory authority responsible for operational and technical safety in the Norwegian Continental Shelf (PSA, 2011b). This means that all floating facilities that carries out any kind of petroleum activity must comply to the PSA’s regulation.

The PSA's Regulations on stability and ballast systems can be found in section 39 and section 62 in PSA (2011b). It also refers to the regulation and requirements issued by the (NMA). The PSA classifies ballast function on a floating facility as a safety function. The following are the main stability and ballast systems' regulations by the PSA and NMA.

NMA REGULATIONS
The main NMA regulations regarding stability and ballast systems include (Sjøfartsdirektoratet, n.d);

- *Regulation 20 December 1991 No. 878 concerning stability, watertight subdivision and watertight/weathertight closing means on mobile offshore units*

This regulation is presented under the PSA regulation Section 62 (Stability)

- *Regulation 20 December 1991 No. 879 concerning ballast systems on mobile offshore units*

This regulation is presented under the PSA regulation Section 39 (Ballast system*)*

PSA Regulations

For floating facilities, PSA regulates ballast systems and stability in section 39 and 62. (PSA, 2011a).

Section 39 Ballast system
Floating facilities shall be equipped with a system that can ballast any ballast tank under normal operational conditions. In the event of unintended flooding of any space adjacent to the sea, it shall nevertheless be possible to ballast. Ballast systems shall be in accordance with Section 2 and Sections 7 through 22 of the Norwegian Maritime Directorate's Regulations relating to ballast systems on mobile facilities

Section 62 Stability
Floating facilities shall be in accordance with the requirements in Sections 8 through 51 of the Norwegian Maritime Directorate's Regulations relating to stability, watertight subdivision and watertight/weathertight closing mechanisms on mobile offshore facilities (in Norwegian only). There shall be weight control systems on floating facilities, which ensure that the weight, weight distribution and centre of gravity are within the design specifications. Equipment and structure sections shall be secured against displacement that can influence stability.

The unit`s survivability is included in the "main support structure" phrase under the facility regulation (Vinnem, 2013). Section 8 is defined as the safety function, relating to the unit`s performance requirement.

Section 8 Safety functions
Facilities shall be equipped with necessary safety functions that can at all times (a) detect abnormal conditions, (b) prevent abnormal conditions from developing into hazard and accident situations, (c) limit the damage caused by accidents. Requirements shall be stipulated for the performance of safety functions. The status of safety functions shall be available in the central control room.

3. METHODOLOGY

This chapter aims to describe methods used in achieving the objective of the thesis. A similar approach to the analytical method recommended by Vinnem (2013) was adopted. However, the main difference is that, the basis of this thesis is on qualitative risk assessment and not on quantitative risk assessment.

Hazard identification was carried out by using both failure mode and effect analysis, FMECA and the standard what-if analysis, SWIFT. The FMECA was adopted to systematically analyse all possible failure modes and its direct reflection on the performance of the ballast system. In addition, the SWIFT was used to compensate for the unidentified hazards in the FMECA (i.e., human related errors). The procedure used to understand the failure, modes and criticality of the ballast system include;

- The ballast system was defined by its system boundaries, functions and, environmental and operational conditions
- Information about the description of the ballast system was acquired mainly from (Hock and Balaban, 1984) and (Hancock 1996)
- Available information was collected from data sources including; RABL datasheet, OREDA and RNNP
- A brainstorming section was carried out by me and some friends in the engineering department to identify failure modes of the components (FMECA) as well as risk that involves human error (SWIFT)
- A generic checklist from HSE (2001) was used to determine identify possible hazard in the SWIFT
- The risk relating to the failure modes were presented by an alternative to the risk matrix that is the Risk priority number (RPN). The RPN was determined by multiplying together the severity (S), occurrence (O) and detectability (D) of the failure modes. Numbers were subjectively assigned to the S, O, D based on my degree of knowledge of the components.

A fault tree was used to determine failure causes of the most critical component (i.e., from the FMECA) of the ballast system as well scenarios that lead to failure. The relationship between the causes and effects of the top event identified.

A barrier analysis was carried out to determine how to prevent, control and mitigate the effects of ballast failure. Five selected past incidents were selected and were subjected to a comprehensive barrier analysis. Two out of the five incidents led to accidents. Information about the cases was retrieved by reading academic papers, books and relevant internet sources. The barriers were divided into; barrier functions, Barrier elements, risk influencing factors of the barriers and their performance requirements. Analysis was then made on the similarities and differences of the events.

Finally, calculations were made on a semi-submersible platform. This was carried out to determine how variations in ballast water could affect the intact stability of a semi-submersible. This illustrates further the impact of ballast failure, for instance in a case where there is pump failure and water cannot be pumped in or out of the tanks or when there are leakages due to structural damage. Numbers were assigned on the dimensions and geometry of the rig. Throughout the calculations, some assumptions and simplifications were made. The main assumptions are as follows;

- The semi-submersible is under operation
- There are usually some differences in layout and structural arrangement between the columns.
- In order to simplify the problem, there are four columns and all the columns are assumed to be identical and circular in cross section.

- The reference semi-submersible has two perimeter pontoons
- Pontoons are below the water line during operation
- The pontoons are rectangular in cross-sections
- The pontoons are filled with 90 % of ballast water

4. BALLAST SYSTEM FAILURE

The draft and heel trim of the vessel is designed to be controlled by the ballast system. In a semi-submersible unit, the lower section of the hull (pontoons) and the lower section of the columns can be filled with sea water and also emptied so as to be able to submerge the vessel (Hancox, 1996). Typically, there should be a consistent change in trim monitoring and motion of the ballast water, due to the change in loading conditions in terms of consumables, materials and liquids.

This chapter describes the ballast system, based on its main components and functions that are important during operations. There is also a description of nine past incidents of semi-submersible rigs. These incidents were because of improper handling and/or failure of the ballast system.

4.1 BALLAST SYSTEM AND FUNCTIONS

As mentioned already, controlling the drift and trim of the semi-submersible is the primary function of the ballast system. In the semi-submersibles, the small water plane area makes it sensitive when there is added weight (Chakrabarti, 2005).

Tinmannsvik et al. (2011), points out that, a 2% mass increase of a semi-submersible will cause about 1m submersion. It is important to note that the semi-submersible stability is also influenced by few other related systems. These systems include, sprinkler/deluge systems, water machinery cooling water, bilge water handling, and fresh water and fuel supply from lower hull storage to upper deck tanks that are ready to use. All these systems affect the stability of the semi-submersible (Hancox 1996). The ballast control room is where these systems are controlled. The ballast control operators are also charged with the supervision of these systems (Hancox 1996).

The subsystems of the ballast system include (Moen, 2012):

- Ballast Tank Configuration
- Pumps, Pipes and Valves
- Electric Power Systems
- Hydraulic Power Systems
- Ballast Control Systems

The Ballast Tanks

Typically, the ballast tanks are placed in the lower columns and hull, and is placed symmetrically within each of the hulls (Hancox, 1996). Even load distribution remains the reason for the symmetric placement. The distribution is done to avoid build-up of bending moments and to avoid shear forces, and also to evenly trim the vessel. The tanks are usually segmented into small volumes, instead of large and less complex designs, to prevent the free surface effect. Risks from a damaged perspective are also minimized by smaller tanks. In the case of accidental flooding, subdividing the tanks minimizes trimming and heeling of levers. (Hancox, 1996).

Pipes

A ballast tank is connected to the piping manifold by a tank line, which serves to empty or fill that tank (Hock and Balaban, 1984). The pipe and valve systems connects the ballast tanks to the pumps. Figure 4-1 presents a typical schematic of piping in a ballast system.

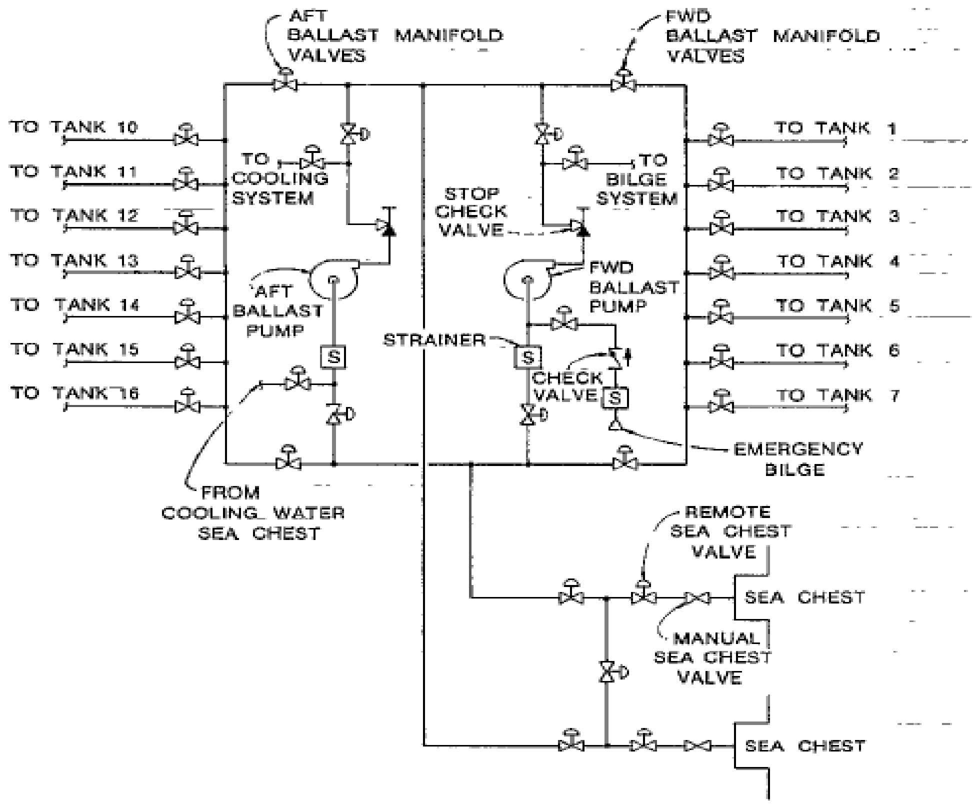


Figure 4-1: Typical schematic of piping in a ballast system. *Source*; (Hock and Balaban, 1984)

The manifold connects the sea chest by the use of remotely operated valves. The system is also fitted with a crossover pipe and valve in order to allow ballast water to be taken or discharged from the sea chests. Regulations demand that there should be separate connections for the sea chests' fire and cooling water system and that of the ballast system (Hock and Balaban, 1984). During design of the piping system, the designer must consider net positive suction head (NPSH) of pumps and to make allowances to recover the rig from a 15 degree inclination (Hock and Balaban, 1984).

Pumps

The manifold is connected to the ballast system sea chest and the pumps. The ballast pumps are used by the piping system to ballast and cool water and also to ballast and run the emergency bilge. These pumps are usually large centrifugal pumps. They use both supplementary instruments and controls, to allow their functions and performance to be controlled and monitored in the control room (Hock and Balaban, 1984)

Valves

The valves operated remotely in the ballast piping system include butterfly valves, sea chest valves etc. The valves are powered by either hydraulic, electric or pneumatic means. Irrespective of the type of power used, some of the valves needs to incorporate failsafe operation to the valve system (Hock and Balaban, 1984). Energy could be stored in the hydraulic accumulators to move valves to its failsafe positions in the event there is loss of control signal to the valve. Figure 4-2 presents a typical schematic of a hydraulic ballast valve system.

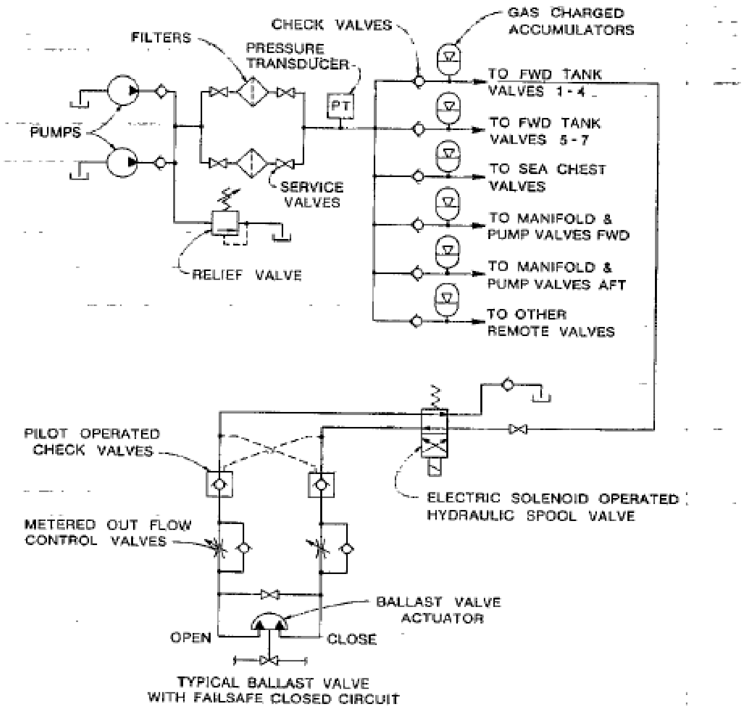


Figure 4-2: Typical schematic of a hydraulic ballast valve system. *Source*; (Hock and Balaban, 1984)

Multiple accumulators and check valves divide the valve system. This is done to avoid that a failure in one part of the system would affect the failsafe operation in other parts. When designing Ballast valves the designer must also consider the valves to be manually operable. Crewmembers are able to operate valves manually by the use of lever arms or by a de-elutchable gearbox. This means that the valve stem must always be visible at the valve during remote and manual operations (Hock and Balaban, 1984). Therefore, positioning of the valve stem is very important.

Electric Power System

The electric power is used to power the ballast system. The electric power system is made up of the uninterrupted power supply (UPS), the main power supply and the emergency backup generator (Moen, 2012). The UPS consists of batteries that are stored charged from the electrical system, an inverter to convert the battery and an electronic switching system that switches from normal to battery power in the case of electric power loss (Hock and Balaban, 1984).

Hydraulic Power Systems

This system consists of a hydraulic accumulator and a hydraulic power unit. In the ballast system, hydraulic power is used to operate the valves (Hock and Balaban, 1984). During operations, the hydraulic power system is continuously pressurized by use of electrical power or hydraulic power generator, so as to ensure that there is consistent pressure. However, in the event of power failure, the hydraulic accumulator automatically provides the required pressure for operation of the ballast valves (Hock and Balaban, 1984)

Ballast Control System

The ballast control system is usually located in the main control room area or in the bridge. The system can be operated both automatically and manually. The automated operation of the ballast system involves the use of computers to operate and monitor the stability of the system (Hancox, 1996). Instruments that indicated the tank levels, pump inlet and discharge pressure, hydraulic system pressure and vessel draft are included in the ballast control panel (Hock and Balaban, 1984). Close supervision of the ballast control system is required to monitor both the ballast level and weight distribution when there is a necessity of manual intervention.

4.2 DESCRIPTION OF SOME PAST INCIDENTS AND ACCIDENTS CAUSED BY BALLAST FAILURE

To prevent near misses and accidents in the future, it is important to acquire information of past events for studies. Such information could be found in journals, investigation reports, newspapers etc. Some loss of stability incidents and accidents are not reported, or lack full information about events leading to the accidents (PSA, 2011c). An example of this issue can be seen in the case of Ocean Developer incident which was under tow from Port Gentil, Gabon to Cape Town when it sank. Detailed information about this incident is difficult to find. The downside to this problem is that detailed studies cannot be carried out to know how and why it happened, especially for peculiar cases. This may be the reason why damage frequency on vessels have not improved over the years (Kvitrud, 2013).

This section contains a description of some accidents that relates to loss of stability and buoyancy of semi-submersibles, with the purpose to give insight on the causes of the accidents. The incidents and accidents are a basis for the establishment of barrier analysis in Appendix B. These accidents are considered to fall into the DFU8 (i.e., incidents that relates to damage to platform structure, stability, anchoring and positioning fault) category in the RNNP (2015), report. However other Defined Situation of Hazard (DFU) categories that are important indicators for loss of stability such as DFU7 (Collision with field-related vessel/facility/shuttle tanker) are not considered for this thesis.

4.2.1 Henrik Ibsen

Brief Description of the rig: Henrik Ibsen a sister rig to Alexander Kielland was owned by Stavanger drilling company. Its main purpose was to serve as a living quarters at Ekofisk field, accommodating about 200 workers (Kulturminne-Ekofisk, n.d). The rig owner A. Gowart-Olsen leased the unit to Philips Petroleum Company. In 1979, they decided to convert the unit into a 600 bed accommodation unit. On March 26, 1980, the rig was towed to Tananger to switch place with Alexander Kielland which was due for major reconstruction and maintenance.

Figure 4-3: The drilling rig Henrik Ibsen. *Source;* Teknisk Ukeblad (n.d)

Although there is little information on Henrik Ibsen, however it is assumed to have the same dimensions as the Alexander Kielland (i.e., its sister rig, The ledger, 1980).

Table 4-1; Principal dimensions, Henrik Ibsen: *Source*; Naess et al., (1982)

Length	103m
Width	99m
Height	40.5 m to main deck
Available Deck Area:	3 X 20m x 17m (1020 m^2) decks and 200 m^2 additional area
Pontoons	5 x 22m diameter pontoons
Columns:	5 x 8.5m diameter columns
Weight	10105 t

Brief Description of Accident: On April, exactly 10 days after Alexander Kielland accident, Henrik Ibsen developed a 20 degrees list. The cause of the initiating event was attributed to human error. Maintenance work was carried on the rig's bracings. It was difficult for the workers to reach the lower bracings and they asked if one of the columns could be trimmed. Ballast water was then pumped into one column. A communication gap led to opened hatches in the column that was pumped with water, hence an ingress of water into the platform (Kulturminne-Ekofisk, 2014). All 57 crewmembers were evacuated.

4.2.2 Ocean Ranger

Brief Description of the rig: The Ocean Ranger was a semi-submersible Mobil Offshore Drilling Unit (MODU) (Sobena, 2007). The unit was designed by the Ocean Drilling Exploration Company (ODECO Coporation), and built by Mitsubishi Heavy Industries in Hiroshima (Sobena, 2007). As at the time the vessel was built, it received a lot of attention because it was the largest available MODU. It had the capacity to operate beneath waters of 1,500 ft and drill as deep as 25,000 ft (Newyork Times, 1982).

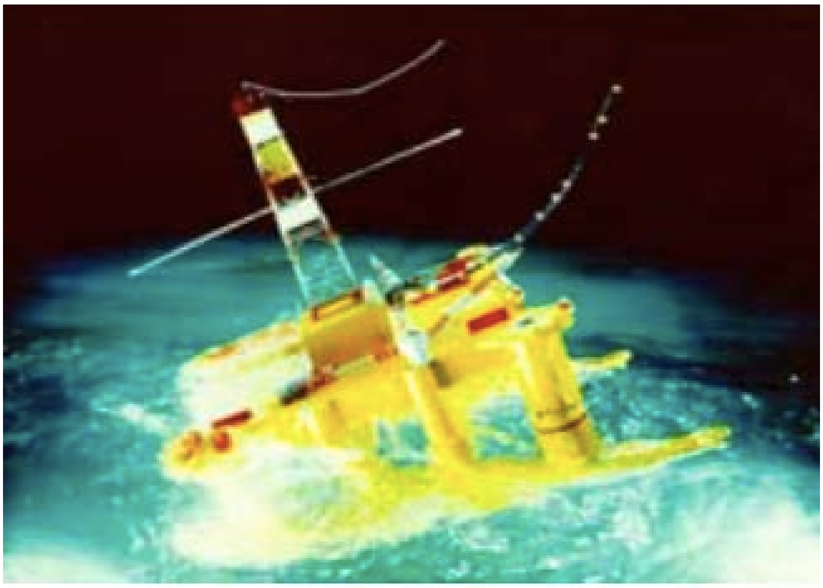


Figure 4-4: The drilling rig Ocean Ranger. *Source;* Moan, (2005)

*Table 4-2;*Principal dimensions, Ocean Ranger: *Source*; USCG, (1982), Songa Offshore, (n.d)

Length	122m
Width	80m
Height	41 m to main deck
Available Deck Area:	3 x 20m x 17m (1020 m^2) pipe decks and 200 m^2 additional lay down area
Pontoons	2 x 122m pontoons
Columns:	4 x 6 m diameter and 4 stabilizing columns of 5.2 m diameter
Operating Displacement	43,521 mt

Brief Description of Accident: On 15 February 1982, while drilling an exploration well off Newfoundland in Canadian waters, the unit capsized (Vinnem, 2013). All 84 crew members on board when it sank all died (PTIL, 2003). The initiating cause was as a result of two portholes that were broken in the ballast control room, caused by wave impact during a storm (Sobena, 2007). The ballasting of the unit was achieved by a number of components in the ballast control system located in a column, 8.5 metres above the mean water line (Sobena, 2007). The control room comprised of an auxiliary manual control board and electrical control board. Gauges were in place to monitor structure movements in water and also portholes to enable the operator to see shifts in depth (Sobena, 2007).

4.2.3 Petrobras P-36

Brief Description of the rig: Petrobras p-36 was a floating production platform operating on the Roncador Field 125 km off the coast of Brazil (Sobena, 2007). Prior to that, In 1995, the 33,000 tonnes vessel was built at Fincantieri Italy as a semi-submersible drilling rig (Mogensen, 2006). It was later converted into a floating production platform from 1997 to 1999. At that time, it was the world's largest oil production unit (Sobena, 2007). It had the capacity to operate in deep water up to 1360m (Mogensen, 2006).

Figure 4-5: The drilling rig Petrobras P-36. *Source*; NASA, (2008)

Table 4-3: Principal dimensions Petrobras P-36: Mace, (n.d)

Length:	112.8m
Width:	77m
Height:	119.1m
Operating Displacement:	34,600 tonnes

Brief Description of Accident: On March 20, 2001 Petrobas P-36 capsized and sank after two explosions in the aft starboard column (Sobena, 2007). At the time of the explosions, 175 people were on the rig and 11 of them died. The unit developed a 16 degrees list, which was enough to allow flooding from the submerged fairlead boxes (Sobena, 2007). Although the rig's sinking was attributed to a combination of several factors however, the initial explosion was as a result of misalignment of the emergency drain tank to the production heater (Sobena, 2007).

4.2.4 BP Thunder Horse

Brief Description of Rig: The Thunder Horse semi-submersible rig was discovered in July 1999. The unit is owned and operated by both BP and Exxon Mobil. Thunderhorse is presently one of the largest deep-water producing fields in the Gulf of Mexico (BP, 2013). The rig consists of Production and Drilling facility with Quarters (PDQ). It has capacity to produce 250,000 barrels of oil per day and 200 mmscfd of gas.

On 11 July 2005, after the event of Hurricane Dennis had subsided, some of the rig's personnel who was earlier evacuated returned to the facility and found the rig wit about a 20 degrees list (PTIL, 2006). The top deck was in the water on the portside.

Figure 4-6: The drilling rig BP Thunderhorse. *Source*; Lyall, (2010)

Table 4-4: Principal dimensions, BP Thunderhorse: *Source*: ABS (n.d); BP (n.d)

Length:	110.08m
Width:	104.96m
Height:	57.5m
Available Deck Area:	Length: 112 m, Breadth : 136 m
Pontoon:	Height: 11.5 m
Columns:	2 @ 22 x 26 m.; 2 @ 22 x 23 m by 36 m. height
Hull Displacement:	129,000 metric tons

Brief Description of Accident: The cause of the incident was as a result of failure associated with the hydraulic control system and its isolation during the hurricane evacuation (SINTEF, 2011). This resulted to partial opening of the vessel, hydraulically actuated valves in the ballast and bilge systems (SINTEF, 2011). In addition, there were multiple cable transits (MCTs) failures in the bulkhead that were seen during assessment of the hull (SINTEF, 2011) Other problems included a bad welding job that left the underwater pipelines full of cracks (Lyall, 2010).

4.2.5 Aban Pearl

Brief Description of Rig: Aban Pearl is a semi-submersible drilling rig designed by Aker H-3 (Aban, n.d). It was constructed by Keppel Corporation, Singapore in 1977. The rig unit was bought for US$211 million by the Indian drilling company Aban Offshore (SINTEF, 2011). It could operate in water up to 380 m and drilling depth of about 7620 m.

Figure 4-7: The drilling rig Aban Pearl. *Source;* Tinmannsvik, (2011)

Table 4-5: Principal dimensions, Aban Pearl: *Source*: Aban (n.d)

Length:	108 m
Width:	67.36 m
Height:	36.6 m
Operating displacement	36470 tonnes

Brief Description of Accident: On May 2010 an incident occurred. The semi-submersible gas production platform sank when drilling at the Dragon 6 gas field off eastern Sucre state, Venezuela. According to SINTEF (2011), the initiating event was because of an uncontrolled intake of water more that the ballast pumps could handle. The port pontoon received water in heavy seas of about 3.7 kilometers, south-west of Point Baline. The rig then lost its stability and sunk. There were no casualties all 95 crew-members were evacuated.

4.2.6 Scarabeo 8

Brief Description of the rig: Scarabeo 8 is a 6th generation semi-submersible drilling rig operated and owned by Saipem (Saipem, n.d). It is designed by Moss Maritime. This unit is capable to operate in deep water of up to 10,000 ft (3,000 m) and its drilling depth capability is up to Up to 35,000 ft (10,660 m) (Saipem, n.d). In addition, the rig is suitable for harsh environment as it can operate in: minimum air temperature of - 20°C and maximum of + 45°C; and minimum water temperature of 0°C and maximum of + 32° (Saipem, n.d).

Figure 4-8: The drilling rig Scarabeo 8. *Source*; OFFSHOREENERGYTODAY, (2012b)

Table 4-6: Principal dimensions, Scarabeo 8: *Source*; Saipem, (n.d)

Length:	118.65 m
Width:	72.72m
Height:	57.15 m to drill floor
Available Deck Area:	Length: 83.20 m, Breadth : 72.72 m, Draught at operation: 23.50 m
Pontoons:	Length: 118.56 m, Breadth : 15.73 m, Depth: 10.15 m
Columns:	4 connected to upper hull
Operating Displacement:	35,304 mt

Brief Description of Accident: On 4 September 2012, the drilling rig was reported to have a list of seven degrees during drilling (PSA, 2013). Although the seven degrees list was not initially life threatening, it became so because of improper handling of the ballast system (PSA, 2013). However, there was no casualties related to the incident.

4.2.7 Floatel Superior

Brief Description of rig: Floatel Superior is a semi-submersible drilling rig with living-quarters and topside storage support (Ptil, 2012). The unit is owned and operated by Floatel International AB of Gothenburg (Ptil, 2012). It was designed and built by Keppel FELS in Singapore. The rig is suitable for harsh environments such as the North Sea. It could operate in water of about 360 m to 420 deep (PSA, 2015).

Figure 4-9: The drilling rig Floatel Superior. *Source;*OFFSHOREENERGYTODAY, (2012b

Table 4-7: Principal dimensions, Floatel Superior: S*ource*: ABS (n.d); DNV (n.d)

Length:	94m
Width:	91m
Height:	57.5
Available Deck Area:	Length: 112 m, Breadth : 136 m
Pontoon	Length: 90 m, Breadth : 64.4 m
Operating displacement	29 179 Mt

Brief Description of Accident: Based on the incident report by Ptil, (2012), on November 6th and 7th, Floatel Superior was damaged in its hull from an unsecured anchor. This led to the entrance of water into two tanks and causing about a 5.8 degrees list. As at the time of the incident, the rig was lying on the Njord field in the North Sea. The Petroleum Safety Authority Norway (PSA) concluded that the damage, which led to the unsecured anchor, had developed over some couple of months. There were several warning signs, which were unattended. During the time of the incident, 374 people where on-board. No casualties were reported as 334 people were evacuated to other nearby installations by a helicopter.

4.2.8 Island Innovator

Brief Description of rig: Island Innovator is a semi-submersible drilling rig owned by Maracc ASA (Islanddrilling, n.d). Presently, Odfjell Drilling provides drilling services and project management under an agreement with Maracc ASA. This unit is capable to operate in water of up to 600 m and drilling depth of about 8000 m) (Islanddrilling, n.d). In addition, the rig is suitable for harsh environment as it can operate at minimum air temperature of - 20°C and maximum of + 35°C

Figure *4-10:*The drilling rig Island Innovator. *Source;* Offshoreenergytoday, (2013)

Table 4-8: Principal dimensions, Island Innovator: S*ource*: Islanddrilling (n.d)	
Length:	104.5 m
Width:	65 m
Height:	57.5
Available Deck Area:	Length: 81 m, Breadth : 65 m
Pontoon:	13 m x 9,75 m (h) (1,3 m radius)
Columns	4 of 13 m x 13 m (1,3 m radius)
Operating displacement	38 040 t

Brief Description of Accident: An incident occurred in May 2013. The rig was docked at Hanøytangen yard outskirts of Bergen where it was undergoing some operational modifications (Offshoreenergytoday, 2013). There was an inflow of water and the rig began to tilt. The leak was because of seawater inlet to a pump room in a pontoon, which was supposed to flow to the ballast tanks (Offshoreenergytoday, 2013). An incident report by Maracc (n.d) state that "*the leakage seems to be due to failure on equipment used by sub-contractors, and not related to the rig itself* ". As at the time of the incident, out of the 100 personnel who were on-board the unit, one worker was slightly injured (Maracc n.d)

4.2.9 Ocean Developer

Brief Description of Accident: It is important to note that, there is generally lack of information for this accident. On 14 August 1995 the ocean developer was under tow from Port Gentil, Gabon to Cape Town when it sank (Vinnem et al, 2006). It sank at about 3600 metres deep off West Africa, close to Cabinda in Northern Angola (Vinnem, 2006).

All 24 crewmembers during the time of the accident survived. The initiating event was assumed to be operation of the ballast system by an inexperienced personnel (Vinnem, 2006)

Table 4-9: Summary of initiating causes of the above incidents due to ballast failure

Rig, Year	Initiating events
Henrik Ibsen, 1980	The cause of the initiating event was attributed to human error. Maintenance work was carried on the rig's bracings. A communication gap led to opened hatches in the column that was pumped with water, hence an ingress of water into the platform (Kulturminne-Ekofisk, 2014)
Ocean Ranger, 1982	The initiating event was as a result of two portholes that were broken out in the ballast control room. This was caused by wave impact during a storm (Vinnem, 2006)
Ocean Developer, 1995	The cause of the initiating event was due to operation of the ballast system by an inexperienced person. The operator was said to have "pushed the wrong button" which led to series of events that resulted to the rig sinking
P-36, 2001	A ruptured emergency drain tank in a column initiated an explosion that damaged a fire water pipe and caused water ingress into the watertight compartments, thruster rooms, pump rooms and killed 11 personnel (Vinnem, 2013)
Thunder Horse, 2005	The cause of the incident was as a result of failure associated with the hydraulic control system and its isolation during the hurricane evacuation (SINTEF, 2011). This caused the ballast and bilge system to open, hence ingress of water.
Aban Pearl, 2010	The initiating event was as a result of an uncontrolled intake of water more that the ballast pumps could handle. The port pontoon received water in heavy seas of about 3.7 kilometers, south-west of Point Baline.
Scarabeo 8, 2012	The initiating event was due to operator error. The inexperienced duty control room operator (COOP) unintentionally opened the aft sea chest valve and ballast tank valve, which allowed ingress of water to the ballast tanks.
Floatel Superior, 2012	According to Ptil, (2012b) the damage, which led to an unsecured anchor, had developed over some couple of months. There were several warning signs, which were unattended. The unsecured anchor created hole in the hull, which permitted ingress of water into the two tanks.
Island Innovator, 2013	The rig developed a leak. This was as a result of seawater ingress to a pump room in a pontoon, which was supposed to flow to the ballast tanks. This led to the rig developing a 4 degrees list (Offshoreenergytoday, 2013).

5. STABILITY OF SEMI-SUBMERSIBLE PLATFORMS

Semi-submersibles are susceptible to loss of buoyancy and stability in several ways. They include collisions, asymmetric load of ballast, explosions, falling objects, fire and explosion, extreme environmental loads, inadequate strength and accidental moveable weight (HSE, 2003). However, this thesis is limited to ballast failures.

Ballasting has significant impact on the stability of a vessel and therefore it is important to consider ballast operations in the stability calculations. This chapter is divided into three sections. The first section discusses freeboard and draft of a semi-submersible rig the second section describes the methodology of stability calculations carried out in appendix B. In section 5.3, involves analysis on the results of the calculation

5.1 FREEBOARD OF FLOATING STRUCTURES

This section entails equations used in the calculation of freeboard for a semi-submersible unit. Assumptions made include four circular columns and two pontoons that provides ballast capacity to the unit; the pontoons are fully submerged (i.e., in operational condition)

A rigid body is considered to be in equilibrium when the resultants of forces and moments acting on it are equal to zero (Gudmestad 2015). For a floating body, the main forces acting on it are its weight and its buoyancy. Buoyancy can be said to be the upward force exerted by the fluid that opposes the weight of an immersed body in water When the two forces are equal, and the centre of gravity, *G*, and buoyance B, are in the same vertical line, there will be equilibrium as illustrated in Figure 5-1

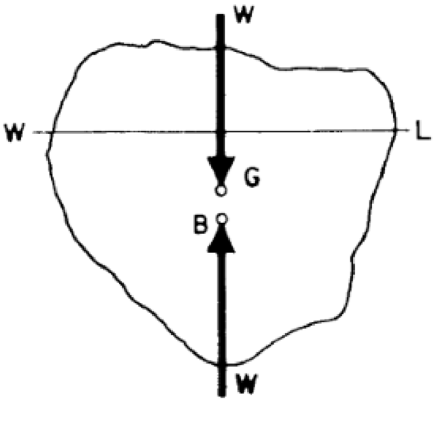


Figure 5-1: Equilibrium of a floating body. *Source:* SNAME, (1988).

For a floating body the distance from the waterline to the deck is known as the freeboard. The freeboard is important in determining the operability of a vessel. The formula for the freeboard could be written as;

$$f = h - d \qquad (5.1\text{-}1)$$

Where

F The freeboard of the vessel (m)

h	The height of the vessel (m)
d	The draft of the vessel (m)

In order to determine the draft of the vessel, the Archimedes principle can be adopted.

$$F_B = F_G \tag{5.1-2}$$

Where

F_B	Buoyance force (N)
F_G	Gravitational force (N)

Let ∇ be the submerged volume of the semi-submersible

$$F_B = \rho_w \cdot \nabla \cdot g$$

$$F_G = m \cdot g$$

Therefore,

$$\rho_w \cdot \nabla \cdot g = m \cdot g$$

$$\nabla = \frac{m}{\rho_w} \tag{5.1-3}$$

Where

∇	Submerged volume of the semi-submersible (m^3)
m	Weight of the semi-submersible (kg)
g	Gravitational acceleration (m/s^2)
ρ_w	Density of saltwater

Freeboard of the Semi-submersible

For this design, the hull structure of the semisubmersible consists of four circular columns, and two pontoons.

In operating condition, all four columns and two pontoons are considered when calculating the draft of the semi-submersible.

The formula for determining the total submerged part of the platform can be written as,

$$\nabla_{semi} = \nabla_{pontoons} + \nabla_{columns} \tag{5.1-4}$$

Where

$$\nabla_{pontoons} = 2(l_p \cdot b_p \cdot h_p)$$

$$\nabla_{columns} = 4(\frac{\pi}{4} \cdot d_c^2)\, h_s$$

Where $\nabla_{pontoons}$ is the submerged volume of the pontoons, $\nabla_{columns}$ is the submerged volume of the circular columns, d_c is the diameter of the column, l_p is the length of pontoon, b_p is the width of pontoon, h_p is the height of pontoon. h_s is the submerged height of the columns that is, the height from the top of the pontoons to the waterline.

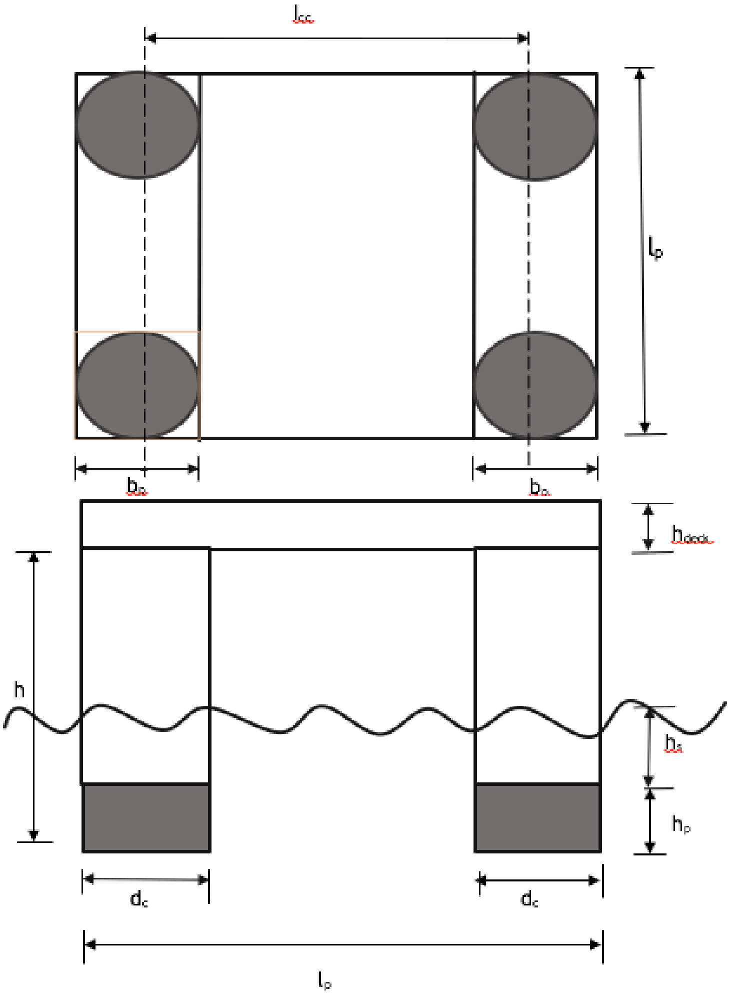


Figure 5-2: Plan view of the semi-submersible

Assuming that $b_p = d_c$ the formula for determining the draft of the semi-submersible d_s is calculated by inserting equation (1.1-4) to equation (1.1-3).

$$\nabla_{semi} = 2(l_p \cdot b_p \cdot h_p) + 4(\frac{\pi}{4} \cdot d_c^2)h_s = \frac{m}{\rho_w}$$

$$h_s = \frac{\frac{m}{\rho_w} - (2 \cdot l_p \cdot b_p)\, h_p}{\pi \cdot d_c^2} \tag{5.1-5}$$

$$d_s = h_s + h_p \tag{5.1-6}$$

Therefore, the freeboard can be calculated by

$$Freeboard = h - \frac{\frac{m}{\rho_W} - (2 \cdot l_p \cdot b_p)\, h_p}{\pi \cdot d_c^2} - h_p \qquad (5.1\text{-}7)$$

Where h is the summation of height of pontoon, height of column and height of deck

5.2 STABILITY CALCULATIONS

Stability requirements for semi-submersibles

Although there are several criteria used in relation to stability of semi-submersibles all over the world, however this thesis considers those set by the Det Norske Veritas (DNV, 2013). Typically, requirements are vital to determine if the semi-submersible is in a safe condition or not. Table 5.1 presents the intact and damaged stability requirements and also requirements for freeboard for metacentric height for column stabilised units such as semi-submersibles).

Table 5-1: Semi-submersible stability requirement (DNV, 2013)

Freeboard	The freeboard must be at least 1.50 m.
Minimum metacentric height, GM	The initial metacentric height, GM, should not be less than 1.0 m.
Static angle of heel (damaged stability)	The static heeling angle can not be more than 17 °
Static angle of heel (intact stability)	The static heeling angle can not be more than 21 °

Generally, the stability of a vessel is dependent on its weight distribution and outer geometry. When a vessel is exposed to the wave forces and currents, a heeling moment is created (Gudmestad, 2015). The ability of the body to return to its initial position after the removal of the external forces (i.e., resisting the overturning forces) is termed to be "stability" (Gudmestad, 2015). These forces may be as a result of weather conditions including, waves and wind; passengers, tow lines, shifting of cargo, or flooding due to damage (Gudmestad, 2015). Stability is usually achieved in large vessels by moving water around in the ballast tanks (Gudmestad, 2015). This ensures that the vessel remains upright and does not lean to one side in the case it is subjected to asymmetrical load or if fuel/mud is taken from the tank on one side of the hull.

Initial stability is the ability of a vessel to resist the initial heel from an upright equilibrium position. Figure 5-3 illustrates that the righting arm $\overline{GZ}$ will help the vessel retain its original position for small angles φ of heel.

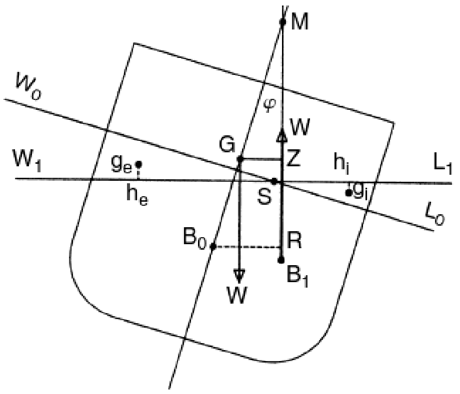


*Figure 5-3:*Important stability properties. Source: Tupper, (2004)

$\overline{GZ}$ is given as,

$$\overline{GZ} \approx \overline{GM} \cdot \sin \delta\varphi \qquad (5.2\text{-}1)$$

Where, $\overline{GM}$ (the metacentric height) is the primary measure for the initial stability of a floating body (Tupper, 2004). It is important to note that in the case of large angles of heel, the righting arm and the metacenter cannot be related with the above equation, as the buoyancy vector no longer passes through the metacenter

From geometry, the metacentric height, is given as;

$$\overline{GM} = \overline{BM} + \overline{KB} - \overline{KG} \qquad (5.2\text{-}2)$$

Where

$\overline{KB}$	The vertical center of buoyancy
$\overline{BM}$	The metacentric radius
$\overline{KG}$	The center of gravity

Intact Stability of the Semi-submersible

The $\overline{KB}$ of the semi-submersible can be calculated as

$$\overline{KB} = \frac{2 \cdot \nabla_{pontoons} \cdot y_p + 4 \cdot \nabla_{column} \cdot y_{subm}}{2 \cdot \nabla_{pontoons} + 4 \cdot \nabla_{columns}} \qquad (5.3\text{-}1)$$

Where

$$y_p = \frac{h_p}{2}$$

$$y_{subm} = h_p + \frac{h_s}{2}$$

y_p	Vertical gravity height of the pontoons
y_{subm}	Vertical gravity height of the submerged part

The formula for the metacentric radius BM, can be calculated by

$$\overline{BM} = \frac{I_{semi}}{\nabla_{Semi}} \qquad (5.3\text{-}2)$$

Where, I_{semi} is the second moment of inertia of the semi-submersible at waterline that can be calculated using the Steiner's formula, see equation (5.3-3).

$$I_{semi} = 4 \cdot [I_{cc} + x_{cc}^2 \cdot A_{cc}] \qquad (5.3\text{-}3)$$

$$I_{semi} = \left[4\left(\frac{\pi \cdot d_c^4}{64}\right) + x_{cc}^2 \cdot \frac{\pi \cdot d_c^2}{4}\right]$$

And

$$I_{cc} = \frac{\pi \cdot d_c^4}{64}$$

$$x_{cc} = \frac{I_{cc}}{2}$$

Where I_{cc} is the moment of inertia for a circle and A_{cc} the area of the column, x_{cc} is the horizontal distance from the center of the circular column to the x-axis as shown in figure 5-4

Therefore,

$$\overline{BM} = \frac{I_{semi}}{\nabla_p + \nabla_c}$$

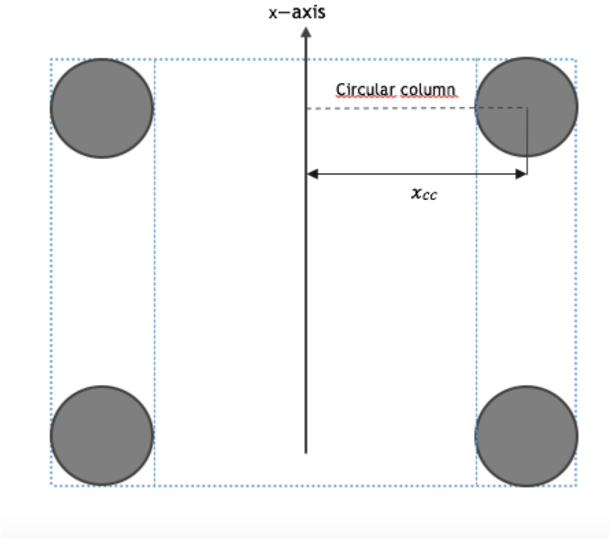


Figure 5-4: The waterline area of the semi-submersible

The center of gravity $\overline{KG}$, of the rig can be written as,

$$\overline{KG} = \frac{2 \cdot M_{pontoon} \cdot y_p + 4 \cdot M_{columnn} \cdot y_{all} + M_{deck} . y_{deck}}{2 \cdot M_{pontoon} + 4 \cdot M_{column} + M_{deck}} \tag{5.3-5}$$

where

$$m_{pontoon} = (b_p \cdot h_p - b_{p\_internal} \cdot h_{p\_internal}) \cdot l_p \cdot \rho_s$$

$$m_{column} = \frac{\pi}{4} \cdot (d_c^2 - d_{c\_internal}^2) \cdot h_c \cdot \rho_s$$

$$m_{semi} = m_{pontoon} + m_{column} + m_{deck}$$

And

$$y_{all} = h_p + \frac{h_c}{2}$$

$$y_{deck} = h_c + h_p + h_d$$

where

$M_{pontoon}$	Mass of one pontoon (Kg)
M_{column}	Mass of one column (Kg)
M_{deck}	Mass of the deck (Kg)

h_c	Overall height of columns
y_{all}	Distance from the pontoon’s top to the middle of the columns (m)
y_{deck}	Distance from the keel to the centre of gravity (m)

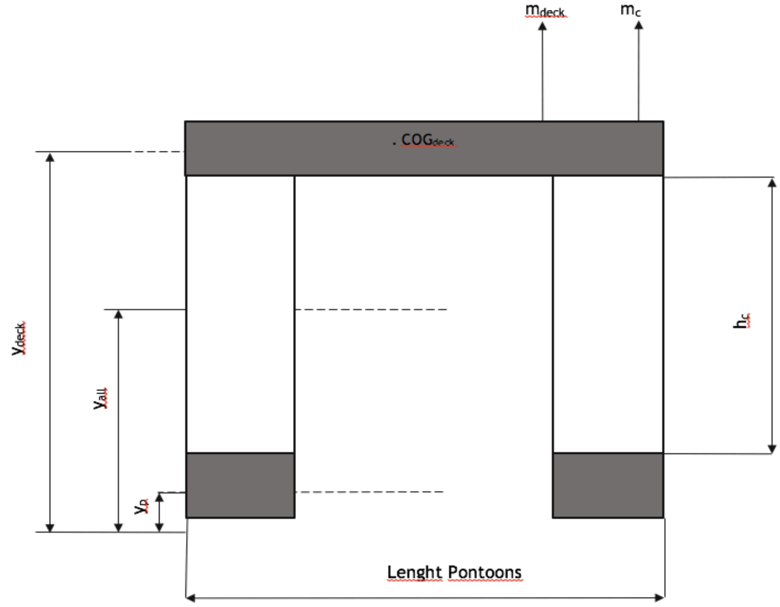


*Figure 5-5:*Parameters used in determining the centre of gravity, KG

In order to determine the formula for the intact stability of the semi-submersible, equation (5.3-1), (5.3-4) and (5.3-5) into equation (5.2-2).
Therefore,

$$\overline{GM} = \frac{2\cdot \nabla_{pontoons}\cdot\ y_p + 4\cdot\ \nabla_{column}\cdot y_{subm}}{2\cdot\nabla_{pontoons} + 4\cdot\nabla_{columns}} + \frac{I_{semi}}{V_p+V_c} - \frac{2\cdot M_{pontoon}\cdot y_p + 4\cdot\ M_{columnn}\cdot y_{all} + M_{deck}. y_{deck}}{2\cdot M_{pontoon} + 4\cdot\ M_{column} + M_{deck}}$$

Intact stability at large angle of heel

For small heeling angles the stability is dominated by the metacentric height ,$\overline{GM}$. These angles are usually in ranges between 0 – 5 ° (Tupper, 2004). However, in cases where the heeling angle is more than 5 °, the rig’s stability is dominated by both the righting arm and the righting moment (Tupper, 2004).

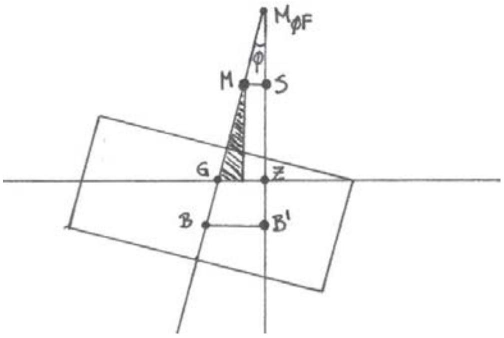


Figure 5-6:. Stability of a semi-submersible at larger angles of inclination. *Source*: Gudmestad, (2015)

The value of the righting moment is as a result of heeling of the rig caused by many phenomena such as; wind, roll due to waves and skew ballast (Gudmestad, 2015). The heeling angle is denoted as φ, and is shown in figure 5-6 above.

The equation for a vessel's righting moment is given as;

$$M_R = \overline{GZ} \cdot \rho_w \cdot \ g \ \cdot \nabla \tag{5.4-1}$$

For small angles

$$M_R = \overline{GM} \cdot \Delta \cdot \ sin\, \varphi \tag{5.4-2}$$

Where

$$\Delta = \mathrm{m} \cdot g$$

Where Δ is the displacement mass. The righting arm equation could be written as (Gudmestad, 2015);

$$\overline{GZ} = \overline{GM} \cdot sin\, \varphi + \frac{1}{2} \cdot \ \overline{BM} \ \cdot \ tan^2\varphi \cdot \ sin\, \varphi \tag{5.4-3}$$

Or

$$\overline{GZ} = \overline{GM} \cdot sin\, \varphi + \frac{1}{2} \cdot \ \overline{MS} \tag{5.4-4}$$

Static Heel Angle of a Vessel Due to additional ballast load

When a semi-submersible platform is subjected to asymmetric load of ballast on one side, it will undergo a heeling angle, ϕ. This is presented in figure 5-7.

The heeling angle can therefore be calculated by using the following formula presented by Tupper (2004)

$$\tan\varphi \ = \frac{\mathrm{GG_1}}{\mathrm{GM_{ballast}}} \tag{5.5-1}$$

$$GG_1 = KG_{old} - KG_{new} \tag{5.5-2}$$

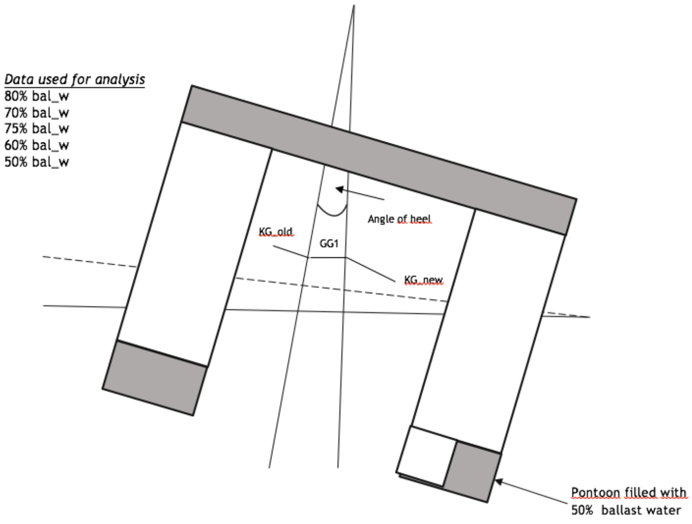


Figure 5-7: Static heeling angle caused by the asymmetric load of ballast

Where GG1 represents the horizontal difference of KG due to the varying ballast.

$$KG_{old} = \frac{M_{pontoon}\,(x_{p1}+x_{p2})+2\cdot M_{column}(x_{c1}+x_{c2})+(M_{deck}.x_{deck})}{2\cdot M_{pontoon}+4\cdot M_{column}+M_{deck}} \qquad (5.5\text{-}3)$$

The different parameters $x_{p1}, x_{p2}, x_{c1}, x_{c2}, x_{deck,} x_{bal1,} x_{bal2}$ in equations (5.5-3) and (5.5-4) are shown in figure 5-8

$$KG_{new} = \frac{M_{pontoon}\,(x_{p1}+x_{p2})+2\cdot M_{column}(x_{c1}+x_{c2})+(M_{deck}.x_{deck})+V_{bal1}\cdot x_{bal1}x+V_{bal2}\cdot x_{bal2}}{2\cdot M_{pontoon}+4\cdot M_{column}+M_{deck}+V_{bal1}+V_{bal2}} \qquad (5.5\text{-}4)$$

Where

$$x_{p1} = \frac{d_c}{2}$$

$$x_{p2} = l_p - \frac{d_c}{2}$$

$$x_{c1} = \frac{h_c}{2}$$

$$x_{c2} = l_p - \frac{d_c}{2}$$

$$x_{deck} = \frac{l_d}{2}$$

$$x_{bal1} = \frac{d_c}{2}$$

$$x_{bal2} = l_p - \frac{d_c}{2}$$

x_{p1}	Horizontal distance from the middle of column 1 to the reference point (m)
x_{p2}	Horizontal distance from the middle of the column 2 to the reference point (m)
x_{c1}	Horizontal distance from the middle of the column 1 to the reference point (m)
x_{c2}	Horizontal distance from the middle of the column 2 to the reference point (m)
x_{bal1}	Horizontal distance from the middle of the column 1 to the reference point (m)
x_{bal2}	Horizontal distance from the middle of the column 2 to the reference point (m)
x_{deck}	Horizontal distance from the middle of the deck to the reference point (m)

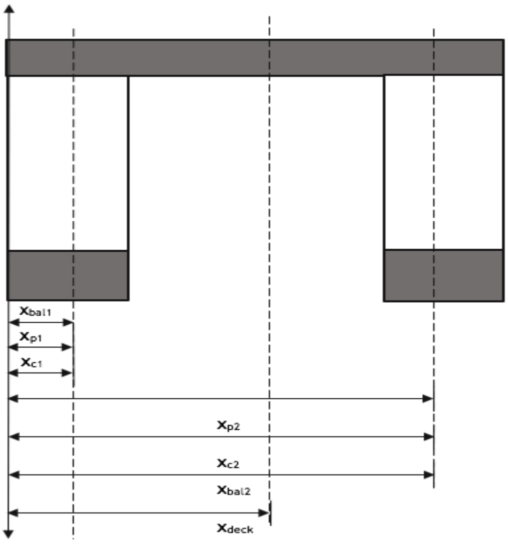


Figure 5-8: KG formula before the presence of heeling moment

5.3 COMMENTS ON RESULTS OF CALCULTIONS

This section presents results of the stability study of a semi-submersible. The results are calculations of freeboard, intact stability and static heeling angle with added ballast. The starboard was filled up with 90% ballast water and the portside with varying percentages (i.e., 80%, 70%, 60%, 50%, 40%, and 30%) of ballast water.

Various important observations were made. There were significant changes when the mass of ballast water in the portside was varied. These changes could be observed in the draft, freeboard, metacentric height and heeling angle.

Draft

Figure 5-9 presents the relationship between the draft and varying ballast water of a semi-submersible during operations. Decrease in the mass of ballast water in the portside means that there will be decrease in draft. The initial draft when the two pontoons were filled with 90% of ballast water was 34.5m. When the ballast water was reduced to 60 %, the draft also reduced to 31 m

Freeboard

Figure 5-10 presents the relationship between freeboard and varying ballast water of a semi-submersible during operations. The initial freeboard when the two pontoons were filled with 90% of ballast water was 13.2 m. However, when there was further 10% reduction on one of the pontoons the freeboard changed from 13.2m to 14.46m. In the case where the ballast water was reduced to about half of its mass, there is 3.725 m increase of freeboard. This is expected, as there is a reduction in weight. It is important to note that the freeboard discussed here, is the freeboard at the middle of the semi-submersible. The minimum freeboard criteria for a semi-submersible is 1.50 (DNV, 2013). This means that the freeboard of the semi-submersible is met in all cases of ballast water variation.

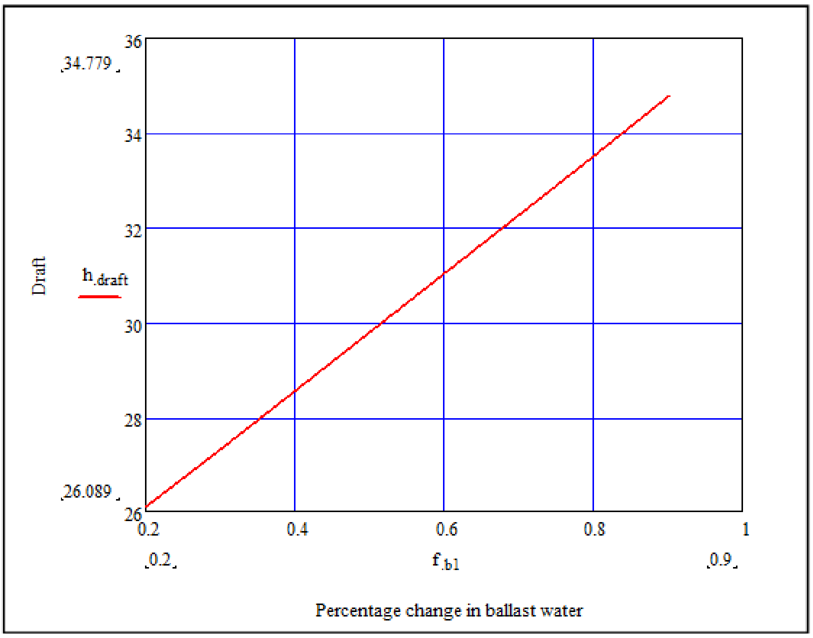


*Figure 5-9:*Variation of draft with change in percentage of ballast water

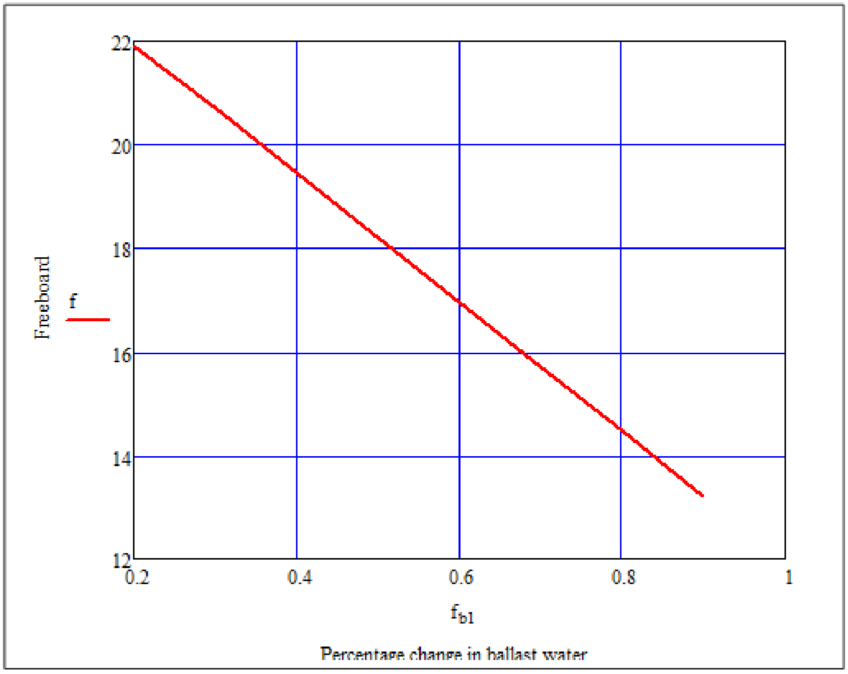


Figure 5-10: Variation of freeboard with change in percentage of ballast water

Intact Stability

The intact stability was 2.95 m when both pontoons were filled with 90% ballast water. However, when there was further 10% (i.e., 80% ballast water) reduction on one pontoons, the intact stability reduced to 2.59m, which is about a 0.51 m reduction. This is presented in figure 5-11. According to regulations, the minimum allowable metacentric height is 1m. This means that in all scenarios where water ballast is varied, the criteria for the metacentric height is met, but for reduced mass of 30%.

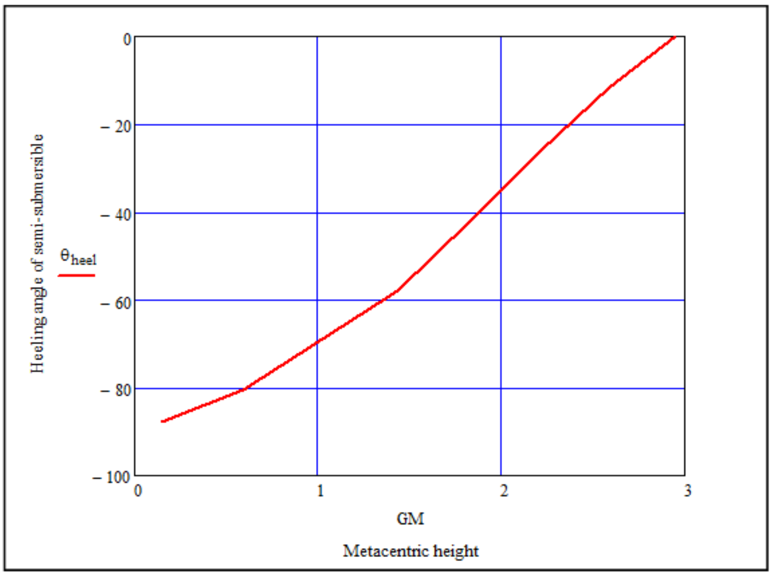


*Figure 5-11:*Variation of metacentric height for different percentages of ballast water

As the rig is subjected to asymmetric load of ballast on one side, it will undergo heeling. In the calculations, the initial heeling angle was 0 when both tanks where filled with ballast water. However, there was a large difference of 11° after one of the tanks had a 10% deduction of ballast water. This is because the volume of a pontoon is 22.500 m^3; therefore, a filling grade of 10% less or more represents a reduction/additional water ballast of 2.250 tonnes. 2.250 tonnes is considerably a large amount of ballast water. Figure 5-12 shows the variation of ballast water with the heeling angle.

According to DNV (2013), in the case of heeling due to steady wind, the maximum heeling angle should not be greater than 17°. This means that a 20 % (i.e., 26°) reduction of ballast water will not meet the requirements. Therefore, for this semi-submersible to meet the requirements, the percentage reduction must not be more than about 15%. Table 5.2 presents the summary of stability calculations.

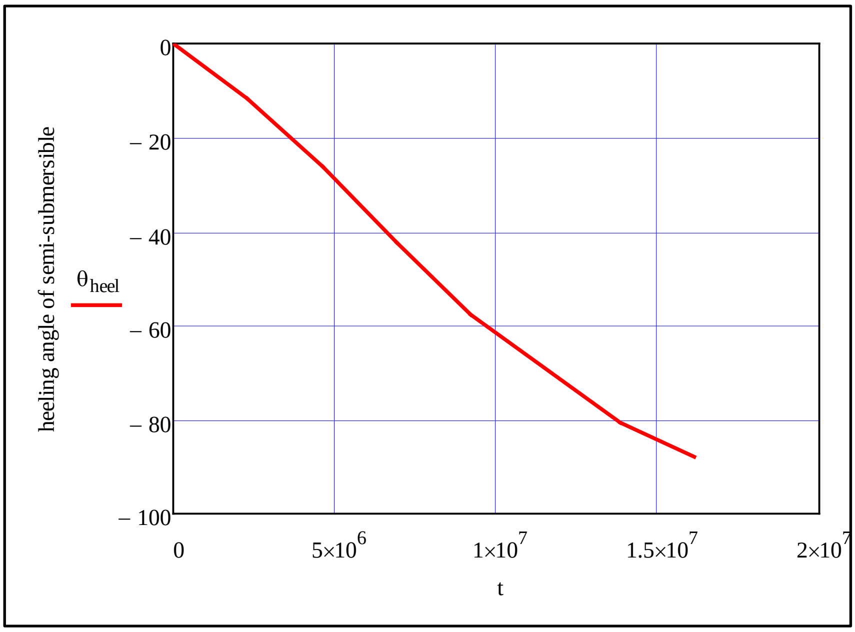


*Figure 5-12:*Variation of ballast water with the heeling angle

Table 5-2:: Summary of stability results

	Change in percentage of ballast water						
	90 %	80 %	70 %	60 %	50 %	40 %	30 %
Freeboard (m)	13.22	14.46	15.70	16.95	18.19	19.43	20.67
Draft (m)	4.78	33.54	32.30	31.05	29.81	27.33	26.10
GM (m)	2.95	2.59	2.21	1.86	1.44	1.02	0.59
Heeling angle (degrees)	0	11.56	26.05	42.23	57.73	70.65	80.58

6. RISK ANALYSIS AND ASSESSMENT OF BALLAST FAILURES

The main purpose of risk assessment is to establish and decide on risk reducing measures (Vinnem, 2013). The decision on the risk reducing measures must be of a structured, systematic and a well documented process. In recent years, focus has been made on models used for risk assessment in the offshore oil and gas industry. The ISO31000 standard: Risk management, principles and guidelines on implementation (ISO 2009; Vinnem, 2013) is commonly used. This approach has been adopted by the PSA and NORSOK Z-013 standard: Risk and emergency preparedness analysis (Standard Norway 2010; Vinnem, 2013). Figure 6-1 presents the main elements of the model. Risk assessment (i.e., Hazard identification, risk analysis and risk evaluation) is the core of the process.

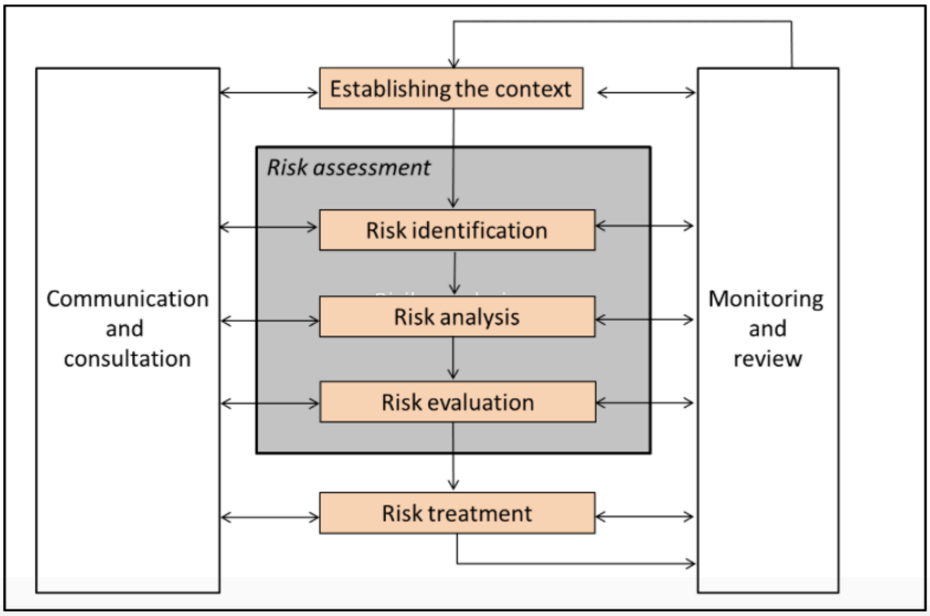


Figure 6-1: The process of risk assessment in ISO31000. *Source*; PSA, (2013)

Although risk assessment has been a common practice over the years. However, with the addition of the new elements (i.e., establishing the context, monitoring and review, and communication and consultation), the established context can be monitored, with regards to its validity about the decision made (Vinnem, 2013).

This chapter aims to evaluate risks involved in ballast operations, by identifying the various hazards causes and consequences. A failure mode effects and criticality analysis (FMECA) is carried out to determine the ability of components in the ballast system to perform its required function. Also, a Structured what-if-checklist (SWIFT) is used to cover issues relating to human errors that the FMECA fails to identify. Section 6.2 presents a fault tree analysis. The fault tree aims to represent the relationship between events and the component failures that may combine to cause an undesirable event. The main component of study is the most critical component identified in the FMECA.

6.1 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 (Vinnem, 2013). Therefore, a comprehensive and well-planned hazard identification is a critical basis for other elements in risk assessment.

Structured What-If Technique

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 (Aven, 2008). 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 (HSE, 2001). 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 6-1:: Generic checklist and hazard brainstorming process of the ballast system

GENERIC CHECKLIST

- **Human factors (incl, Operating errors**
- **Maintenance**
- **Malfunction of equipment**
- **Utility failure**
- **Measurement errors**
- **Emergency operation**
- **Integrity failure**
- **External factors**

HAZARD BRAINSTORMING

1. **Faulty ballast system design**
2. **Vessel monitoring system failure**
3. **Pump Failure**
4. **Valve failure**
5. **Pipe failure**
6. **Remote System operation failure**
7. **Tank overpressure or under pressure**
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 6-2:*Hazard identification based on SWIFT. *Source;* HSE, (2001)

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/deballasting**
1	**Causes**	Unfavorable 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

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 (Rausand, 2011). 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 Rausand (2011). Table 6.3 presents a breakdown of the ballast system analysed in Appendix C, figure C-2

*Table 6-3:*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

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 its 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, Risikonivå 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;

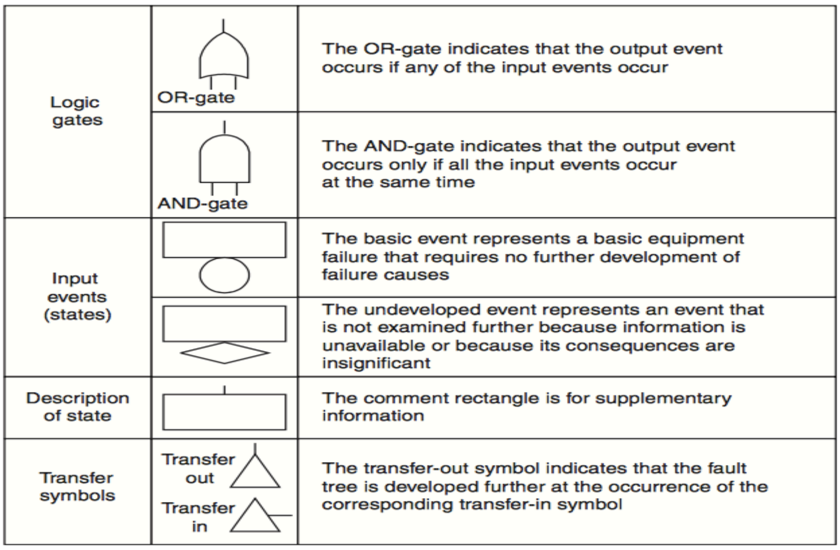
- It is assumed that one components fails at a time
- Human error contributions are neglected
- Failure modes analysed are the more frequent failure modes but not the modes analysed comprehensive
- The identified failure causes are not a full assessment of all the failure modes of the components

Based on the analysis in Appendix C figure C-2, the component with the highest ranking are the valves, hence the most critical.

6.2 FAULT TREE ANALYSIS

A fault tree analysis is a logical representation of the relationship between events and component failures that may combine to cause an undesirable event (e.g., failure of a barrier system and failure of the system's component) (Aven, 2008). The top event of the tree represents an undesirable event and the basic events represents different component failures, human errors, or failures that results from external load (e.g, extreme environmental conditions). Symbols are used to show the relationship between basic events and the state of the system (Aven, 2008). Table 6.4 shows symbols and interpretation, of a fault tree.

Table 6-4: Symbols and interpretations of a fault tree. *Source*; Rausand and Høyland, (2004)



Logic gates	OR-gate	The OR-gate indicates that the output event occurs if any of the input events occur
	AND-gate	The AND-gate indicates that the output event occurs only if all the input events occur at the same time
Input events (states)		The basic event represents a basic equipment failure that requires no further development of failure causes
		The undeveloped event represents an event that is not examined further because information is unavailable or because its consequences are insignificant
Description of state		The comment rectangle is for supplementary information
Transfer symbols	Transfer out Transfer in	The transfer-out symbol indicates that the fault tree is developed further at the occurrence of the corresponding transfer-in symbol

The cause of ballast system failure is analysed using fault tree approach by considering the stability calculations result presented in section 5.2 (detailed calculation in Appendix B). From the stability calculation is observed that the semi-submersible will lose its stability at the following criteria; Freeboard (15.70m), Draft (32.30m), GM (2.21m) Heeling angle (26.1m), for a percentage difference in the mass of ballast water between tank 1 and tank 2. Appendix C Figure C-3 shows the fault tree analysis of the ballast system considering an event where the heeling angle is 26.1 degrees. Thus, the top event is instability of semi due to ballast system failure at 26.1 degrees heeling angle. It should be noted that loss of ballast water in the ballast tank results to a critical heeling angle. Also based on the results from the FMECA analysis the ballast valve is considered critical, hence the fault tree is aimed to analyse the valve.

6.3 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 (Sintef, 2015). Although there may be possibility of a single failure to occur, it should however 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 (Sintef, 2015).

Safety barriers are established and implemented with the aim of preventing, controlling and mitigating the effects of a hazardous event (Sklet, 2006). Figure 6-2 presents a typical approach for classifying barriers

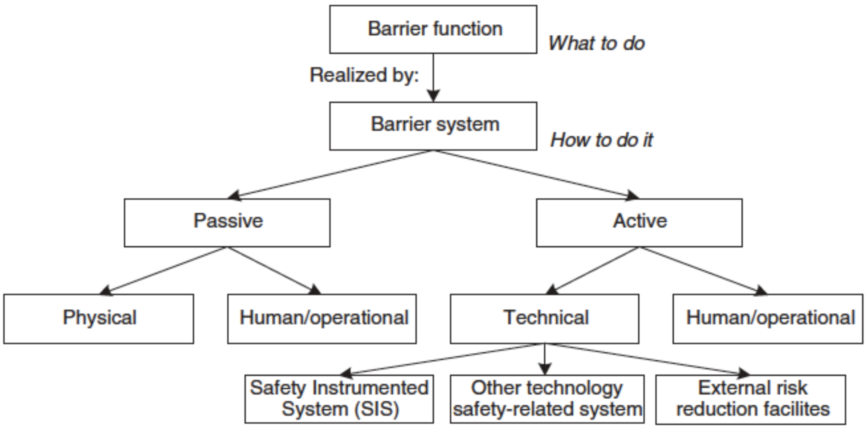


Figure 6-2: Barrier classification. *Source*; Sklet, (2005)

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 (PSA, 2013). Barrier management includes systems, processes solutions and measures that must be readily available to reduce risk by the implementation and follow–up of barriers (PSA, 2013).

This chapter aims to describe barrier management in terms of barriers that can prevent or reduce effects of unwanted events during operations of semi-submersibles. Section 6.2.1 defines and describes some important terms used in barrier management. 6.2.2 presents a detailed barrier analysis of some notable past accidents /incidents reviewed in appendix D

6.3.1 Terminology used in barrier analysis

A barrier function is defined as the role or purpose of a barrier (DNV-GL, 2014). If the barrier function is achieved, there should be a significant effect on the hazard and event sequence. A range of personnel, system structures are needed to realise the barrier functions. These measures include technical, operational and organisational barrier elements (DNV-GL, 2014).

According to DNV-GL, (2014), **technical barrier element** includes; Structures, Engineering systems, or other design features that performs barrier functions when required. Technical barriers are of two types, the functional/active barrier elements and the structural/passive barriers. Active barriers are referred to technical barriers that are dependent on operator actions, control system and some energy source to perform its functions. on the other hand, barriers do not need operator actions, control systems or energy sources as they are measures integrated in the platform design. Example of technical barrier elements include; Ballasting system, thrusters, position keeping system, hull, watertight, anchor lines, compartments, valves, etc. **Operational barrier element** involves tasks carried out by an operator that realises several barrier functions. Operation barrier element may include; Operate MOB boat, ballasting operations, emergency and controlled disconnect, weather monitoring, monitor ships etc. The personnel carrying out the task are referred to as **organizational barrier element** (DNV-GL, 2014).

Risk Influencing factors (RIFS)

It is vital to know the risk influencing factors (RIF) when carrying out barrier analysis. A RIF otherwise known as barrier performance influencing factors can be defined as "*an aspect of a sys- tem or an activity that affects the risk level of the object*" (Øien (2001). It is can also be defined as "a relatively stable condition that influences risk" (Rausand, 2011). Generally, the overall risk is controlled by the control of changes of the risk-influencing factor (Vinnem, 2013). An example of the application of the risk influencing factor during operations of semi-submersibles is; if a worker is carrying out a manual inspection of the flood detection function in the ballast control room, possible factors that may influence the personnel's performance include,

- Manual inspection procedures
- work organization and work patterns
- Training and experience of operators
- Motivation of operators etc.

Appendix D table D.8 presents the groups in which the RIFs are grouped into and the description of each of the RIFs. It is important to note that what is usually considered to be barriers by some definition can also be considered to be RIFs (Vinnem, 2013). Figure 6-3 shows the relationship between barrier factors, barrier elements and RIFs for a valve in a wrong position after maintenance.

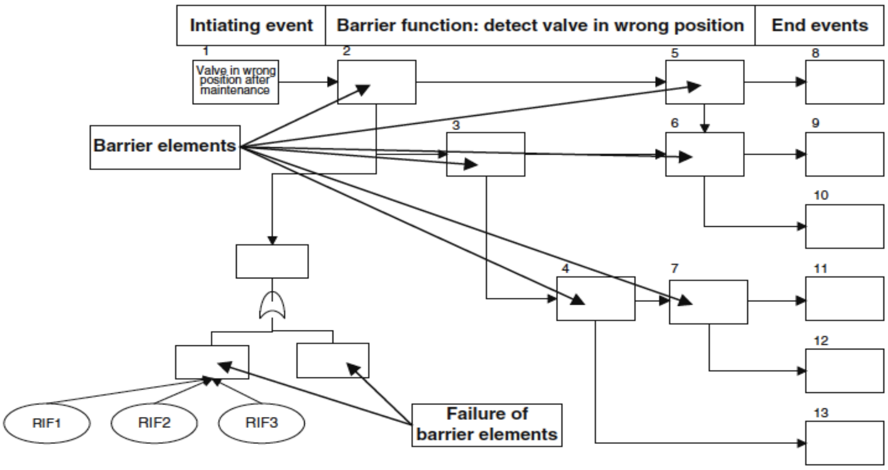


*Figure 6-3;*Relationship between barrier function, elements and RIFs. Source; PSA, 2013

Performance requirements

In the context of safety barriers, performance means properties a barrier must have to ensure that individual barrier and its function is effective (PSA, 2013)
"*Performance requirements must be set for technical, operational and organisational barrier elements*" (PSA, 2013). It includes aspects such as, reliability, capacity, availability, integrity, ability to withstand load, mobilization time, robustness, and effectiveness. According to PSA, (2013) Figure 6-4 presents an approach describe performance requirements in relation to technical, operational and organizational barriers. Performance requirements relates only to the barrier elements whose quality they intend to ensure. This means that for instance, a specific course could be required to be taken by personnel to acquire the right job performance needed to realise a barrier function.

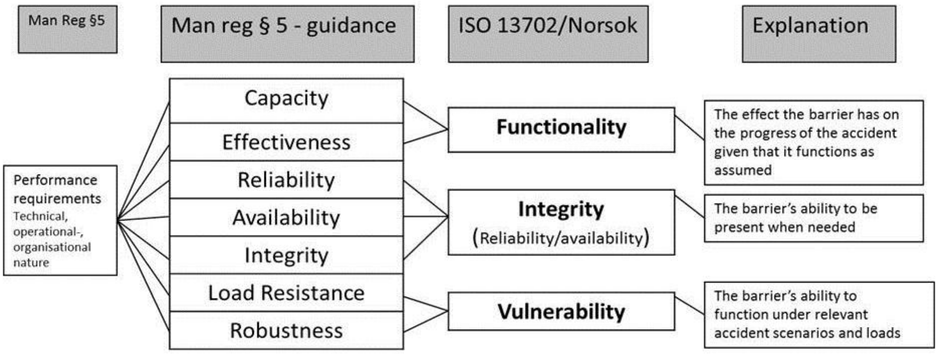


Figure 6-4: Categorizing performance requirements for technical, operational and organisational barrier elements. *Source* (PSA, 2013)

6.3.2 Barrier performance of some notable accidents/incidents

This section describes some notable accidents/near accidents caused by ballast failure on semi-submersible rigs in the past. A generic diagram adopted from COWI, (2003) is used to understand the event sequence that leads to each of the selected accidents/incident. A detailed barrier analysis is presented in Appendix D. The tables in Appendix D describes barrier functions (BF), barriers systems/elements (BS) and risk influencing factors (RIF) of these accidents. The performance of the BFs, BSs, RIFs are also evaluated.

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 COWI, (2003). Figure 6-5 shows a sample and description of the barrier diagram used in this thesis to provide an event sequence overview leading to the accident.

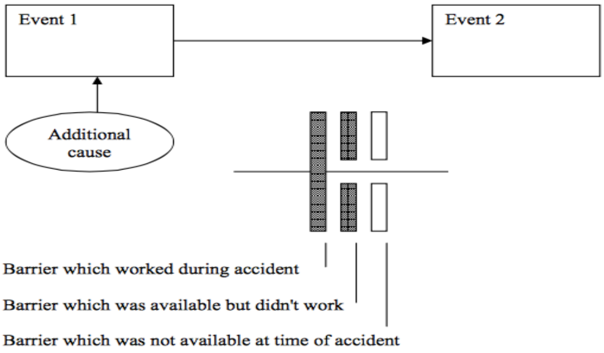


Figure 6-5: Barrier diagram

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.

Appendix D presents a detailed barrier analysis of accidents/incidents of five selected rigs. An overview of the analysed accident is shown in table 6.5.and the barrier performance summary in table 6.6

Table 6-5: 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 6-6: 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 error is significant as it is 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.

7. DISCUSSION

Notwithstanding the importance of well-functioning ballast systems on semi-submersibles, very few research has been undertaken within the field of buoyancy loss and stability caused by ballast failure during operations. The main objective of this thesis is to evaluate the risks involved during ballast operations of a semi-submersible, and to recommend on ways by which risk can be reduced during operations of the system.

In order to be able to evaluate risk that involves ballast failure of a semi-submersible during operations, it is important to understand to an extent the components and subsystem that make up the ballast system. This is presented in section 4.1. The main subsystems identified include: ballast tank configuration; Pipe, Pumps and valves; Ballast control system; Hydraulic power system; Electric power system. Calculations are also made to illustrate the effects of asymmetric changes in ballast tank level on the heeling of semi-submersibles and consequent failure. Chapter 5 describes the methodology of stability calculations carried out in appendix B. The dimensions used for the calculations are determined from similar rig dimensions in chapter 4 and suggestions from the thesis supervisor. Throughout the calculations, some assumptions and simplifications are made. The main assumptions include: Environmental loads are not considered; The semi-submersible is in an operational mode; There are differences in layout and structural arrangement between the columns. In order to simplify the problem, there are four columns and all the columns are assumed to be identical and circular in cross section. The reference semi-submersible has two rectangular pontoons and the pontoons are below the water line during operation. The starboard is filled up with 90% ballast water and the portside with varying percentages (i.e., 80%, 70%, 60%, 50%, 40%, and 30%) of ballast water.

Draft

Results shows that a decrease in the mass of ballast water in the portside means that there will be decrease in draft. The initial draft when the two pontoons were filled with 90% of ballast water was 34.5m. When the mass of ballast water reduced to 70 %, the draft also reduced to 32.3 m

Freeboard

The initial freeboard when the two pontoons are filled with 90% of ballast water is 13.2 m. However, when there is a further 20% reduction on one of the pontoons the freeboard changes from 13.2m to 15.7 m. In the case where the ballast water is reduced to about half of its mass, a 3.725 m additional increase in freeboard is observed. This is expected, as there is a reduction in weight. It is important to note that the freeboard discussed here, is the freeboard at the middle of the semi-submersible. The minimum freeboard criteria for a semi-submersible is 1.50 (DNV, 2013). This means that the freeboard of the semi-submersible is met in all cases of ballast water variation.

Stability

The intact stability is calculated to be approximately 2.95 m when both pontoons were filled with 90% ballast water. However, when there is further 30% (i.e., 70% ballast water) reduction on one pontoon, the intact stability reduced to 2.59m, which is about a 0.51 m reduction. According to regulations, the minimum allowable metacentric height is 1m. This means that in almost all scenarios where water ballast is varied, the criteria for the metacentric height is met, except in the scenario with 30% mass of ballast water in one pontoon.

Static Heeling Angle

The results show a significant difference on the heeling angle in all scenarios. As the rig is subjected to

asymmetric load of ballast on one side, it will undergo heeling. In the calculations, the initial heeling angle is 0 when both tanks are filled with 90% ballast water. However, there was a large difference of 11° after one of the tanks had a 10% deduction of ballast water. This is because the volume of a pontoon is 22.500 m^3; this means that a filling grade of 10% less or more represents a reduction/additional water ballast of 2.250 tonnes. 2.250 tonnes is considerably a large amount of ballast water
According to DNV (2013), in the case of heeling due to steady wind, the maximum heeling angle should not be greater than 17°. This means that a 20 % (i.e., 26°) reduction of ballast water will not meet the requirements. Therefore, for this semi-submersible to meet the requirements, the percentage reduction must not be more than about 15%.

Qualitative risk assessment

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 lack full information about events leading to the accidents. The downside to this problem is that detailed studies are not carried out to know how and why it happened, especially for peculiar cases. This may be the reason why damage frequency on vessels have not improved over the years. Figure 5-1 presents a distribution of causes of nine selected past incidents/accidents that led to loss of buoyancy or stability of a semi-submersible.

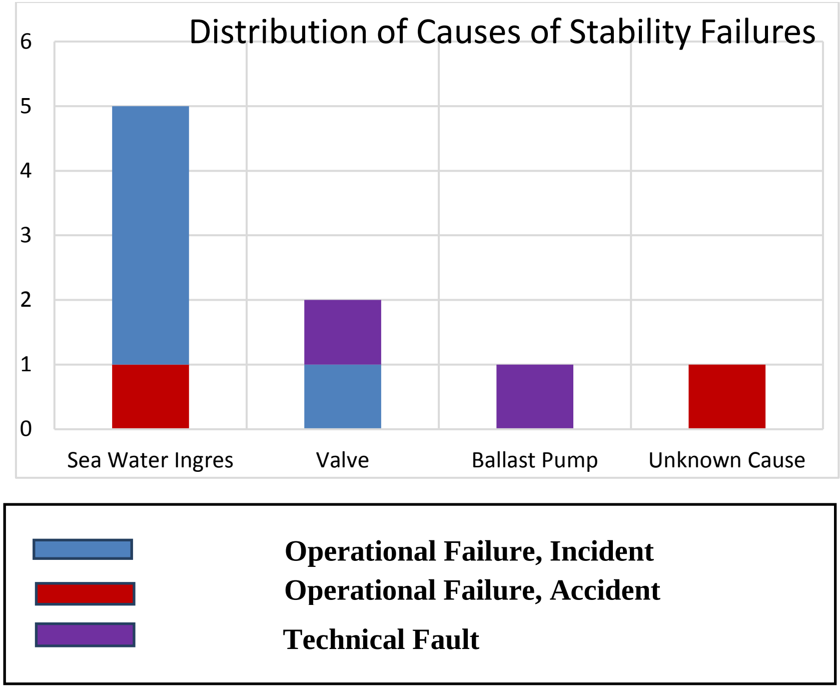


Figure 7-1: Distribution of causes of stability failures

A more detailed information about some semi-submersibles and its dimensions is given in chapter 4. Five out of the nine incidents/accidents, were caused by uncontrolled water ingress. This is in line with the conclusion by Tinmannsvik et al. (2011) 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 Vinnem et al., (2006) 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 error. These accidents could have been prevented if the human interface (i.e., designers, operators and organization) had followed the guidelines in PSA (2011a) regulations discussed in section 2.3.2. 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 thesis 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 analyse all possible failure modes and its direct reflection on the performance of the ballast system. The SWIFT is used to compensate for unidentified hazards in the FMECA (i.e., human related errors). The hazard identification is based on brainstorming by utilising a generic checklist of elements in the ballast system. Table 6.2 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 /deballasting
- Loss of watertight integrity or weathertight 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 6.2 for recommendations)

A FMECA is carried out to reveal and analyse failure modes, failure causes and failure effects on the main components of the ballast system. Information about the failure rates are 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 my degree of knowledge of the components. A detailed FMECA is presented in Appendix C figure C-2. Findings show that failure of valve to "*close on demand*" with an RPN of 60 is the most critical.

The cause of ballast system failure is analysed using fault tree approach by considering the result of stability calculations presented in in Appendix B. From the stability calculations, it is observed that the semi-submersible will lose its stability at the following criteria presented in table 7.1, for a percentage difference in the mass of ballast water between tank 1 and tank 2.

Table 7-1: Scenario with 70% of ballast water in tank 2

Freeboard	**Draft**	**GM**	φ_{heel}
15.70	32.30	2.21	26.05

Thus, it is imperative to evaluate the failure of this semi-submersible. Appendix C Figure C-3, shows the fault tree analysis of the ballast system considering an event where the heeling angle is 26.1 degrees. Thus, the top event is "*instability of semi due to ballast system failure at 26.1 degrees heeling angle*".

It should be noted that loss of ballast water in the ballast tank results to a critical heeling angle. Also based on the results from the FMECA analysis the ballast valve is considered critical, hence the fault tree is aimed to analyse the valve. Appendix C Figure C-3 presents a detailed chain of scenarios that could lead to ballast valve failure.

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 thesis is the barrier management. A detailed description is presented in section 6.3 and Appendix D presents a detailed barrier analysis of five selected rigs accidents/incidents. The analysis shows the direct implications of barrier failures in terms of technical operational and organisational elements. Human error is 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 7-2 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 organisational 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

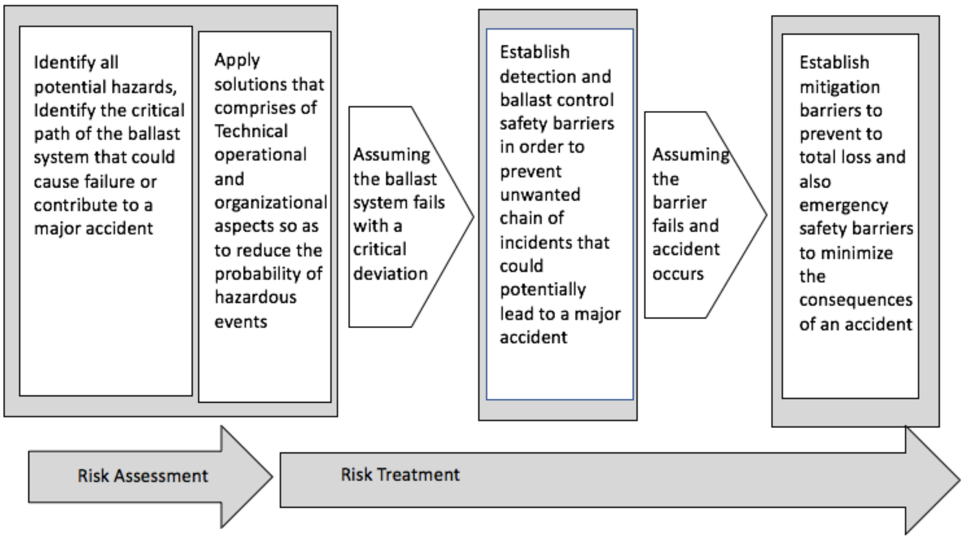


Figure 7-2; Established approach of risk reduction

8. CONCLUSIONS

The consequences of instability of semi-submersible rigs during operation are considered to be severe. Hence, this master thesis is focused on integrating operational stability calculations of a semi-submersible rig with risk analysis. The purpose of this thesis 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.

In this thesis, 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 Henrik Ibsen, Ocean Ranger, Ocean Developer, Petrobras P-36, Aban Peal, Thunder Horse, Floatel Superior, Scarabeo 8 and Island Innovator. Prior to the risk assessment, stability calculations should be carried out to evaluate the semi-submersible rig against stability criteria. This intends to show the ability of the rig to withstand abnormal conditions related to ballast and the effect of variations in the amount of ballast water on the heeling angle. The results of the stability calculations show that more than approximately 15% reduction of ballast water in one of the tanks (where the other is full) could lead to unacceptable heeling angle by regulation requirements.

Critical events were identified in the FMECA relating to changes in the amount of ballast water. Also components in the ballast system were analysed, and based on finding, the failure 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 valve regarded here is the valve 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 undesirable 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.

RECOMMENDATIONS

The study efforts and other past studies related to risk analysis of the ballast system of a semi-submersible during operations have identified fundamental knowledge 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 thesis 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.

REFERENCE

ABS Records, (2001). [Online]: General Statistics. Available: http://www.eagle.org/safenet/record/record_vesseldetailsprinparticular?Classno=07113112 [Assessed 4th March 2017]

Aven, T. (2008). *Risk analysis: assessing uncertainties beyond expected values and probabilities*. Chichester, England: Wiley.

Baunan, T. (1996). FPSO‘s Fulfilling Shelf Requirements by the Maritime Approach Offshore Technology Conference (OTC), Houston.

BP, (2013). [Online]: Thunder Horse Field Fact Sheet. Available: http://www.bp.com/content/dam/bp-country/en_us/PDF/Thunder_Horse_Fact_Sheet_6_14_2013.pdf [Accessed: 23rd February, 2017]

Bsee, (N.D). [Online]: ACCIDENT INVESTIGATION REPORT. Available: https://www.bsee.gov/sites/bsee.gov/files/reports/safety/050708-pdf.pdf [Accessed: 19th February, 2017]

Chakrabarti, (2005). Handbook of Offshore Engineering, Vol. 1 & Vol.2. Elsevier Ltd.

Chen, H., Moan, T., and Verhoeven, H. (2007). Safety of dynamic positioning operations onmobile offshore drilling units. Reliability Engineering and System Safety 93.

COWI (2003). Ageing rigs: Review of major accidents, Causes and barriers, Report no. P-055481-

B32.Available:http://www.ptil.no/getfile.php/131893/z%20Konvertert/Health%2C%20safety%20and%20environment/Safety%20and%20working%20environment/Dokumenter/2003cowiag-ingrigs_nov03.pdf [Assessed 6th March 2017]

Deepwater, (1991). [Online]: Transocean Richardson. Available: http://www.deepwater.com/Documents/RigSpecs/Transocean%20Richardson.pdf [Assessed 12th June, 2017]

Deepwater, (2017). [Online]: Transocean Spitsbergen. Available: http://www.deepwater.com/Documents/RigSpecs/Transocean%20Spitsbergen.pdf [Assessed 12th June, 2017]

DNV.GL, (2013). [Online]: Scarabeo 8. Available: http://vesselregister.dnvgl.com/VesselRegister/vesseldetails.html?vesselid=26777 [Assessed 4th March 2017]

DNV-GL, (2014). [Online]: Barrier Management in Operation for the Rig Industry; Good Practices. Available:https://www.google.no/url?sa=t&rct=j&q=&esrc=s&source=web&cd=2&cad=rja&uact=8&ved=0ahUKEwiYsoXq07zSAhWJ8ywKHTi8AJoQFgguMAE&url=https%3A%2F%2Fwww.rederi.no%2Fen%2FDownloadFile%2F%3Ffile%3D12349&usg=AFQjCNGYwhUCTM13NFrxjyjqyaiEIXJxjA [Assessed 4th March 2017]

Floatel, (2017). [Online]: Floatel Superior. Available: http://www.floatel.se/fleet/floatel-superior [Assessed 4th March 2017]

Gudmestad, (2015). Marine Technology and Operations; WIT-Press, Southampton, UK

Hancox, M. (1996). Oilfield Seamanship Series Volume 7: Stability and Ballast Control. Oilfield Publications Limited, Ledbury, England. 133

Haug et al, (2009). [Online]: Advances in rig design. Available: http://www.offshore-mag.com/articles/print/volume-69/issue-7/drilling-__completion/advances-in-rig-design.html [Assessed 12th June, 2017]

Hock and Balaban, (1984). Fault analysis of a semisubmersible's ballast control system. Offshore technology conference Houston, Texas.

HSE, (2001). [Online]: Marine risk assessment. Available: http://www.hse.gov.uk/research/otopdf/2001/oto01063.pdf [Assessed 12th June, 2017]

HSE, (2003). [Online]: Review of the risk assessment of buoyancy loss (RABL) project. Available: http://www.hse.gov.uk/research/rrpdf/rr143.pdf [Assessed 12th June, 2017]

Island Innovator, (2017). [Online]: Semi Submersible Drilling Rig. Available: http://www.islanddrilling.no/bilder/filer/IslandInnovator.pdf [Assessed 4th March 2017]

Ismail, Z., Kuan, K. K., Othman, S. Z., Hing, L. K., Yee, K. S., Chao, O.Z. and Shirazi, S. (2014). Evaluating accidents in the offshore drilling of petroleum: regional picture and reducing impact. Measurement, vol. 51, p.18-33.

ISO, (2009). ISO/IEC 31000 risk management, principles and guidelines on implementation.

Kaiser, M.J., Snyder, B. and Pulsipher, A.G., (2013). Offshore Drilling Industry and Rig Construction Market in the Gulf of Mexico. [online]: Louisiana: Bureau of Ocean Energy Management. Available at: http://www.data.boem.gov/PI/PDFImages/ESPIS/5/5245.pdf [Accessed 10 March 2017]

Kulturminne-Ekofisk, (n.d). [Online]: Hva skjedde med "Henrik Ibsen"? Available: http://www.kulturminneekofisk.no/modules/module_123/templates/ekofisk_publisher_template_category_2.asp?strParams=8%233%23%23857&iCategoryId=405&iInfoId=0&iContentMenuRootId=&strMenuRootName=&iSelectedMenuItemId=1266&iMin=685&iMax=686. [Assessed 14th March, 2017]

Kumar, S., Chattopadhyay, G. and Kumar, U. (2007). Reliability improvement through alternative designs: a case study. *Reliability Engineering & System Safety*, 92(7), 983-991.

Kvitrud, A, (2013). Modifications of the PSA regulations based on case studies of stability accidents. 32th International Conference on Ocean, Offshore and Arctic Engineering.

Leonhardsen, R. L., Ersdal, G., and Kvitrud, A. (2001). Experience and Risk Assessment of FPSOs in Use on the Norwegian Continental Shelf: Description of Events. International Offshore and Polar Engineering Conference, Stavanger.

Lotsberg I, Olufsen O, Solland G, Dalane JI, Haver S (2004) Risk assessment of loss of structural integrity of a floating production platform due to gross errors. Marine Struct 17:551–573

Lyall S, (2010). [Online]: "In BP's Record a History of Boldness and Costly Blunders". *New York Times*. Available: http://www.nytimes.com/2010/07/13/business/energy-environment/13bprisk.html [Accessed 23rd February, 2017]

MacDonald, A., Cain, M., Aggarwal, A. K., Vivalda, C., and Lie, O. E. (1999). Collision Risks Associatedwith FPSOs in Deep Water Gulf of Mexico. Offshore Technology Conference (OTC), Houston.

Mace, (n.d). Petrobras Platform P-36 Explosions, Brazil http://www.mace.manchester.ac.uk/project/research/structures/strucfire/CaseStudy/HistoricFires/Other/petrobras.htm [Accessed 23rd February, 2017]

Maracc, (2013). [Online]: Incident on the Island Innovator. Available: http://otc.nfmf.no/public/news/13701.pdf [Assessed 4th March, 2017]

Mogensen, V. (ed.) (2006). Worker Safety under Siege: Labor, Capital, and the Politics of Workplace Safety in a Deregulated World. Armonk, NY: M.E. Sharpe

Moen, H. F. (2012). [Online]: Reliability Assessment of Safety Instrumented Systems: An Application Example for A Ballasting System. Master’s thesis, Norwegian University of Science and Technology. Available: https://brage.bibsys.no/xmlui/bitstream/handle/11250/240856/629214_FULLTEXT01.pdf?sequence=1&isAllowed=y [Assessed 4th March, 2017]

Naess, A. A., Haagensen, P. J., Lian, B., Moan, T., & Simonsen, T. (1982). [Online]: Investigation of the Alexander L. Kielland Failure - Metallurgical and Fracture Analysis. Offshore Technology Conference Available: https://www.onepetro.org/conference-paper/OTC-4236-MS[Assessed 14th March, 2017]

Nesje, J. D., Aggarwal, R. K., Petrauskas, C., Vinnem, J. E., Keolanui, G. L., Hoffman, J., and McDonnell, R. (1999). Risk Assessment Technology and its Application to Tanker Based Floating

Production Storage and Offloading (FPSO) Systems. Offshore Technology Conference (OTC), Houston

NASA, (2008). [Online]: System Failure Case Studies; That Sinking Feeling. Available: https://sma.nasa.gov/docs/default-source/safety-messages/safetymessage-2008-10-01-losofpetrobrasp36.pdf?sfvrsn=4 [Accessed 23rd February 2017]

NASA, (2011). [Online]: Porthole to Failure: The sinking of the Ocean Ranger. Available: https://sma.nasa.gov/docs/default-source/safety-messages/safetymessage-2011-12-12-thesinkingoftheoceanranger-vits.pdf?sfvrsn=4 [Accessed 23rd February 2017]

New York Times, (1982). [Online]: ”80 feared dead as oil drilling rig reportedly sinks in north Atlantic”. Available: http://www.nytimes.com/1982/02/16/world/84-feared-dead-as-oil-drilling-rig-reportedly-sinks-in-north-atlantic.html?scp=7&sq=sinks%20in%20Atlantic&st=cse [Accessed 23rd February 2017]

New York Times, (2010). [Online]: “In BP’s record, A history of Boldness and Costly Blunders”. Available: http://www.nytimes.com/2010/07/13/business/energy-environment/13bprisk.html [Accessed 23rd February, 2017]

Nilsen, L.R. (2005). Marine systems in risk analyses for mobile units. M.Sc.thesis, University of Stavanger.

Norsk Olje & Gass (2004) Norwegian Oil and Gas Application of IEC 61508 and IEC 61511 in

the Norwegian Petroleum industry. Available:https://www.norskoljeoggass.no/Global/Retningslinjer/HMS/TekniskSikkerhet/070%20-%20Application%20of%20IEC%2061508%20and%20IEC%2061511.pdf
Assessed 12th June, 2017]

Ocean Rig, (2013). [Online]: Semi Submersible Rigs.
Available: http://www.ocean-rig.com/fleet/semi_submersible_rigs [Accessed 12th June, 2017]

OGP (2006). Guideline for managing marine risks associated with FPSOs. The International Association of Oil & Gas Producers (OGP).

Offshore Energy Today, (2012a). [Online]: "Floatel Superior Tilts, Statoil evacuates workers". Available: http://www.offshoreenergytoday.com/floatel-superior-tilts-statoil-evacuates-workers-norway/[Accessed 23rd February 2017]

Offshore Energy Today, (2012b). [Online]: "Scarabeo 8 Tilting: PSA Norway discovers serious breaches of regulations". Available: http://www.offshoreenergytoday.com/scarabeo-8-tilting-psa-norway-discovers-serious-breaches-of-regulations/ [Accessed 23rd February, 2017].

Offshore Energy Today, (2013). [Online]: "Island Innovator Tilts in Hanoytangen. Workers Evacuated". Available: http://www.offshoreenergytoday.com/island-innovator-tilts-in-bergen-workers-evacuated/ [Accessed 23rd February, 2017]
OREDA, (2009). Offshore reliability data handbook/prepared bySINTEF.5thedition,2009.

OLF070 (2004). *Application of IEC 61508 and IEC 61511 in the Norwegian Petroleum Industry*.

PSA (2001). [Online]: P-36 Inquiry Commission Final Report. Available:
http://www.psa.no/getfile.php/13148/z%20Konvertert/Health%2C%20safety%20and%20environment/Safety%20and%20working%20environment/Dokumenter/p_36_petrobas2.pdf [Assessed 23rd February, 2017]

PSA (2011a). Guidelines for application for Acknowledgement of Compliance (AOC) for mobile facilities intended for use in the petroleum activities on the Norwegian Continental Shelf.

PSA, (2011b). Framework regulations. Petroleum Safety Authority, Norwegian Pollution Control Authority and the Norwegian Social and Health Directorate, Stavanger

PSA (2011c). Deepwater Horizon-ulykken: Vurderinger og anbefalinger for norsk petroleumsvirksomhet. Petroleum Safety Authority Norway

PSA, (2013). [Online]: Principles for barrier management in the petroleum industry.
Available: http://www.ptil.no/getfile.php/1319891/PDF/Barrierenotatet%202013%20engelsk%20april.pdf [Assessed 12th June 2017]

PSA, (2015) [Online]: Trends in risk level in the petroleum activity – Summary report 2015, Norwegian Continental shelf: Available: http://www.psa.no/getfile.php/PDF/RNNP%202015/RNNP-2015%20Summary%20report.pdf [Assessed 4th March 2017]
PSA, (2012). [Online]: Report from the investigation of the listing of Floatel Superior, 7 November 2012 on the Njord field. Petroleum Safety Authority Norway; 2013. Available: http://www.ptil.no/enforcement-notices/notification-of-or der-after-investigation-of-stability-incident-on-floatel-superior-7-novem ber-2012-article9284-892.html [Assessed 4th March 2017]

PSA, (2013). [Online]: "Causal relationships and measures associated with structural and maritime incidents on the Norwegian Continental Shelf". Available: *http://www.psa.no/getfile.php/PDF/RNNP_2013/12%209%202014%20Causal%20relationships%20and%20measures%20associated%20with%20structural%20and%20maritime%20incidents%20on%20the%20NCS.pdf* [Assessed 23rd February, 2017]

PSA, (2015). [Online]: Consent to use Floatel Superior as a flotel for the Goliat field. Available: http://www.psa.no/consents/consent-to-use-of-floatel-superior-as-a-flotel-for-the-goliat-field-article11338-890.html [Assessed 4th March 2017]

Ptil, (2011). [Online]: Regulations relating to design and outfitting of facilities, etc. in the petroleum activities (the facilities regulations). Available: http://www.ptil.no/getfile.php/1319041/Regelverket/Innretningsforskriften-2011_e.pdf [Accessed: 12th June, 2017]

Ptil, (2012). [Online]: Investigation Report; Report from the investigation of the listing of *Floatel Superior*, 7 November 2012 on the Njord Field. Available: http://www.ptil.no/getfile.php/1319801/Tilsyn%20på%20nettet/Granskinger/2012_1727_Granskingsrapport%20Floatel%20Superior%20-%20engelsk.pdf [Assessed 23rd February, 2017]

Rausand, M. and Høyland, A. (2004): System Reliability Theory. 2nd ed. John Wiley and Sons Ltd., New York, NY.

Rausand, M. (2011). Risk Assessment: Theory, Methods, and Applications. Wiley and Sons Inc. Hoboken, New Jersey, 1st edition

Rig Aban Pear, (1977). [Online]: Semi-Submersible Drilling Unit. Available: http://www.aban.com/aol/pdffiles/rigabanpearl.pdf [Assessed 4th March 2017]

Rocha, G. C., do Amaral Vasconcellos, J. M., and Frutuoso e Melo, P. F. F. (2010). Functional Reliability Study of the Electrical Power System, Automation System and Ballast system to Maintain the Balance of a FPSO Platform. Society of Petroleum Engineers (SPE) Conference, Rio de Janeiro, Brazil.

Saipem, (2013). [Online]: Scarabeo 8. Available: http://www.saipem.com/en_IT/static/documents/1612spm_scara8_web.pdf [Accessed 18th February, 2017]

Sandberg L., Hvidsten J., Folke-Olsen E. L., Ellingsund H. A., Nilssen J., Allegra G. (2012). [Online]: Event Investigation Report, Ballast Incident Scarabeo 8 http://www.eninorge.com/Documents/Rapporter/Investigation_report_Scarabeo%208-4%20September.pdf [Assessed 14th March, 2017]

SINTEF, (2011). [Online] Deepwater Horizon-ulykken: Årsaker, lærepunkter og forbedringstiltak for norsk sokkel Available: http://www.ptil.no/getfile.php/1314466/PDF/Deepwater%20Horizon%20-%20SINTEF%20-%20Vedleggsrapport_mai%202011.pdf [Assessed 14th March, 2017]

SINTEF, (2015). [Online]: Towards a holistic approach for barrier management in the petroleum industry. Available: https://www.sintef.no/globalassets/project/pds/reports/sintef-a26845-towards-a-holistic-approach-for-barrier-management-in-the-petroleum-industry-final.pdf [Assessed 12th June, 2017]

Sklet, S. (2006). Safety Barriers: Definition, classification, and performance. Journal of Loss Prevention in the Process Industries.

Sklet, S., Aven, T., Vinnem, J. E. (2006). Barrier and operational risk analysis of hydrocarbon releases (BORA-Release) Part I. Method description. Journal of Hazardous Materials , 137(2):681–691

Sobena, (2007). [Online]: Marine Systems and Ocean Technology. Available: http://www.sobena.org.br/msot/downloads/MS&OT_v3_n1_jun2007.pdf [Assessed 23rd February, 2017]
Songa Offshore, (2014). [Online]: Songa Delta; Modified Ocean Ranger design Column Stabilized Semi-Submersible Rig and Equipment Overview. Available: http://www.songaoffshore.com/Documents/Songa_Delta_-_Exec_Sum__Oct_2014_.pdf [Assessed 4th March 2017]

Standard Norway, (2010). Risk and emergency preparedness analysis, NORSOK Standard Z-013

Teknisk Ukeblad, (n.d). [Online] Riggulykker Available: https://www.tu.no/artikler/disse-riggene-gikk-det-galt-med/236201 [Assessed 14th March, 2017]

The Ledger, (1980). [Online] 57 evacuated from tilted oil rig. Available: https://news.google.com/newspapers?id=LIQwAAAAIBAJ&sjid=4PoDAAAAIBAJ&pg=6900%2C2180631[Assessed 14th March, 2017]

Tinmannsvik, R., Albrechtsen, E., Bråtveit, M., Carlsen, I., Fylling, I., Hauge, S., Haugen, S., Hynne, H., Lundteigen, M., Moen, B., Okstad, E., Onshus, T., Sandvik, P., and /Oien, K. (2011). [Online]: Deepwater Horizon-ulykken: Årsaker, lærepunkter og forbedringstiltak for norsk sokkel. *SIN- TEF Report*. Available: https://www.sintef.no/globalassets/upload/konsern/media/deepwater-horizon---sintef---vedleggsrapport_mai-2011.pdf [Assessed 23rd February, 2017]
Tronstad, L. (2009). The Use of Risk Analysis in Design: Safety Aspects Related to the Design and Operation of a FPSO. Society of Petroleum Engineers (SPE) Conference, Stavanger.

Tupper, E. C. (2004). Introduction to Naval Architecture: Naval architecture, Jordan Hill, GBR, Butterworth-Heinemann, 464 p.

Uscg, (1982). [Online]: Marine Casualty Report; MODU Ocean Ranger O.N. 615641, 'Capsizing and Sinking in the Atlantic Ocean, on 15 February 1982 with Multiple Loss of Life'. Available: https://www.uscg.mil/hq/cg5/cg545/docs/boards/oceanranger.pdf [Assessed 4th March, 2017]

Vinnem JE, Haugen S (1987) Risk assessment of buoyancy loss—introduction to analytical approach, Paper to City University. In: International conference on mobile units, London, 14–17 Sept 1987

Vinnem, J. E. (2000). Offshore Technology Report. Operational safety of FPSOs: Initial Summary Report. HSE Health & Safety Executive.

Vinnem J.E, Kvitrud A. and Nilsen L.R., (2006) [Online]: Stabilitetssvikt av innretninger på norsk sokkel - Metodikk for risikoanalyse Available: http://www.ptil.no/getfile.php/131246/z%20Konvertert/Helse%2C%20miljø%20og%20sikkerhet/Hm3s-Aktuelt/Dokumenter/2006stabilitetssviktforinnretningerpånorsksokkel.pdf [Accessed: 23rd February, 2017]

Øien, K, (2001). Risk indicators as a tool for risk control. Reliability Engineering and System Safety, 74. 129–145.

Østby, E., Berg, M., and Festøy, B. (1987). Ballast System Failures And Other Faulty Weight Conditions. RABL Risk Assessment of Buoyancy Loss and Other Faulty Weight Conditions. PPS3:Ballast System

APPENDIX A

CHAPTER 1 FIGURES

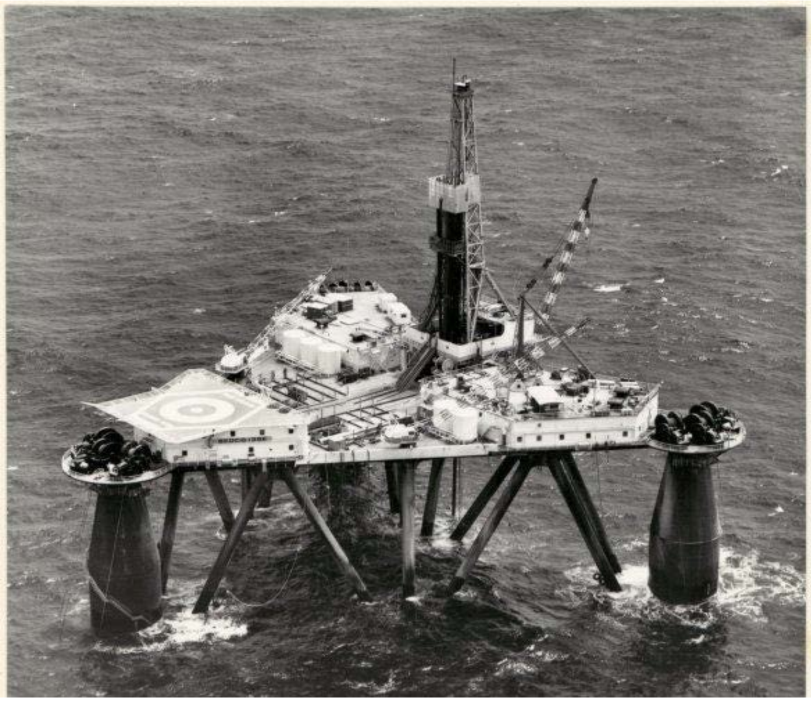


Figure A- 1; SEDCO 135 1st generation rig type built in 1967. Source; Kaiser et al., (2013)

Figure A- 2; Essar Wildcat. A 2nd generation Aker H-3 submersible developed in 1977. *Source;* Kaiser et al., (2013)

Figure A- 3; Ocean Patriot, a 3rd generation Bingo 3000 semisubmersible, built in 1983. *Source;* Kaiser et al., (2013)

Figure A- 4; Transocean Richardson, a 4th generation semi-submersible, built in 1988/1991. *Source;* Deepwater, (n.d ,a)

Figure A- 5; Leiv Eirikssen, a 5th generation semisubmersible, built in 2001. Source; Ocean Rig (n.d)

Figure A- 6; Transocean Spitsbergen a 6th generation semisubmersible Aker H-6e Semi-submersible , built in 2009. *Source;* Deepwater, (n.d ,b)

APPENDIX B

STABILITY CALCULATIONS

density of seawater $\rho_w := 1025 \frac{kg}{m^3}$

density of steel $\rho_s := 7850 \frac{kg}{m^3}$

width of pontoon $b_p := 24m$

height of pontoon $h_p := 13m$

height of deck $h_d := 5m$

height of column $h_c := 35m$

diameter of column $d_c := b_p$

$h_d + h_c + h_p = 53\,m$

moment of inertia $I_{cc} := 48m$

$I_{cc} + d_c = 72\,m$

lenght of deck $l_d := I_{cc} + d_c$

width of deck $b_d := I_{cc} + d_c$

lenght of pontoon $l_p := I_{cc} + d_c$

$h := h_c + h_p$

mass of deck $m_d := 35000000kg$

massof pontoon $m_p := 5000000kg$

mass of column $m_c := 5000000kg$

total mass $m_s := m_p + m_c + m_d$ $\quad m_s = 4.5 \times 10^7\,kg$

percentage variation of ballast water tank 1 $f_{b1} := \begin{pmatrix} 0.9 \\ 0.8 \\ 0.7 \\ 0.6 \\ 0.5 \\ 0.3 \\ 0.2 \end{pmatrix}$

percentage of ballast water 2 $f_{b2} := 0.90$

volume of ballast tank 1 $V_{bal1} := h_p \cdot b_p \cdot l_p \cdot f_{b1}$

volume of ballast tank 2 $V_{bal2} := h_p \cdot b_p \cdot l_p \cdot f_{b2}$

total volumn of ballast $V_t := V_{bal1} + V_{bal2}$

mass of ballast tank 1 $m_{bal1} := V_{bal1} \cdot \rho_w$

mass of ballast tank 2 $m_{bal2} := V_{bal2} \cdot \rho_w$

total mass of ballast $m_{balt} := V_t \cdot \rho_w$

$$m_{bal1} = \begin{pmatrix} 2.072 \times 10^7 \\ 1.842 \times 10^7 \\ 1.612 \times 10^7 \\ 1.382 \times 10^7 \\ 1.151 \times 10^7 \\ 6.908 \times 10^6 \\ 4.605 \times 10^6 \end{pmatrix} kg \qquad m_{bal2} = 2.072 \times 10^7\, kg \qquad m_{balt} = \begin{pmatrix} 4.145 \times 10^7 \\ 3.914 \times 10^7 \\ 3.684 \times 10^7 \\ 3.454 \times 10^7 \\ 3.224 \times 10^7 \\ 2.763 \times 10^7 \\ 2.533 \times 10^7 \end{pmatrix} kg$$

height of submerged column
$$h_s := \left[\frac{4 \cdot \left(\frac{m_s}{\rho_w} + V_t - 2 \cdot l_p \cdot b_p \cdot h_p \right)}{\pi \cdot d_c^{\,2} \cdot 4} \right]$$

freeboard $f := h - h_s - h_p$

draft $h_{draft} := h_s + h_p$

$$f = \begin{pmatrix} 13.221 \\ 14.463 \\ 15.704 \\ 16.946 \\ 18.187 \\ 20.67 \\ 21.911 \end{pmatrix} m \qquad h_s = \begin{pmatrix} 21.779 \\ 20.537 \\ 19.296 \\ 18.054 \\ 16.813 \\ 14.33 \\ 13.089 \end{pmatrix} m \qquad h_{draft} = \begin{pmatrix} 34.779 \\ 33.537 \\ 32.296 \\ 31.054 \\ 29.813 \\ 27.33 \\ 26.089 \end{pmatrix} m$$

volume of semi-submersible $V_{sub\_semi} := \frac{m_s}{\rho_w} + V_t$

volume of pontoon $V_p := 2 \cdot l_p \cdot b_p \cdot h_p$

volume of column $V_c := (4) \cdot \left(\frac{\pi}{4} \cdot {d_c}^2 \right) \cdot h_s$

$$V_c = \begin{pmatrix} 3.941 \times 10^4 \\ 3.716 \times 10^4 \\ 3.492 \times 10^4 \\ 3.267 \times 10^4 \\ 3.042 \times 10^4 \\ 2.593 \times 10^4 \\ 2.368 \times 10^4 \end{pmatrix} m^3 \qquad V_p = 4.493 \times 10^4 \, m^3$$

vertical gravity height of pontoon $y_p := \frac{h_p}{2}$ $\quad y_p = 6.$

vertical height of the submerged column $y_c := \frac{h_s}{2} + h_p$

distance from the keel to the centre of gravity $y_{deck} := h_c + h_p + 5.m$

$$y_c = \begin{pmatrix} 23.889 \\ 23.269 \\ 22.648 \\ 22.027 \\ 21.406 \\ 20.165 \\ 19.544 \end{pmatrix} m$$

distance from the keel to the centre of ballast water 1 $y_{bal1} := \frac{h_p}{2} \cdot f_{b1}$

distance from the keel to the centre of ballast water 2 $y_{bal2} := \frac{h_p \cdot f_{b2}}{2}$

$$KB := \overrightarrow{\left[\frac{V_p \cdot y_p + V_c \cdot y_c}{\left(V_p + V_c\right)}\right]}$$

$$x_{cc} := \frac{\left(I_{cc}\right)}{2}$$

second momen of inertia $I_{semi} := \left(\left(\frac{\pi \cdot {d_c}^4}{64} + {x_{cc}}^2 \cdot \frac{\pi \cdot {d_c}^2}{4}\right)\right) \cdot 4$ $\quad I_{semi} = 1.107 \times 10^6 \, m^4$

metacentric radius $BM := \overrightarrow{\left(\frac{I_{semi}}{V_p + V_c}\right)}$

$$BM = \begin{pmatrix} 13.131 \\ 13.49 \\ 13.87 \\ 14.272 \\ 14.697 \\ 15.629 \\ 16.141 \end{pmatrix} m$$

centre of gravity $KG := \overrightarrow{\left[\frac{2 \cdot m_p \cdot y_p + 4 \cdot m_c \cdot y_c + \left(m_d \cdot y_{deck}\right) + m_{bal1} \cdot y_{bal1} + m_{bal2} \cdot y_{bal2}}{\left(2 \cdot m_p + 4 \cdot m_c + m_d + m_{balt}\right)}\right]}$

metacentric height $GM := BM + KB - KG$

$$GM = \begin{pmatrix} 2.953 \\ 2.593 \\ 2.221 \\ 1.835 \\ 1.435 \\ 0.594 \\ 0.152 \end{pmatrix} m$$

horizontal distance from the middle of column 1 to ref point $x_{p1} := \frac{d_c}{2}$

horizontal distance from the middle of column 2 to ref point $x_{p2} := l_p - \frac{d_c}{2}$

horizontal distance from the middle of column 1 to ref point $x_{c1} := \frac{d_c}{2}$

horizontal distance from the middle of column 1 to ref point $x_{c2} := l_p - \frac{d_c}{2}$

horizontal distance from the middle of column 1 to ref point $x_{bal1} := \frac{d_c}{2}$

horizontal distance from the middle of column 1 to ref point $x_{bal2} := l_p - \frac{d_c}{2}$

horizontal distance from the middle of deck to ref point $x_{deck} := \frac{l_d}{2}$

$$KG1 := \frac{(m_p)\cdot(x_{p1} + x_{p2}) + 2\cdot m_c\cdot(x_{c1} + x_{c2}) + (m_d\cdot x_{deck})}{(2m_p + 4m_c + m_d)}$$

$$KG1 = 36\,m$$

$$KG2 := \overrightarrow{\left[\frac{(m_p)\cdot(x_{p1} + x_{p2}) + 2\cdot m_c\cdot(x_{c1} + x_{c2}) + (m_d\cdot x_{deck}) + m_{bal1}\cdot x_{bal1} + m_{bal2}\cdot x_{bal2}}{(2m_p + 4\cdot m_c + m_d + m_{bal1} + m_{bal2})}\right]}$$

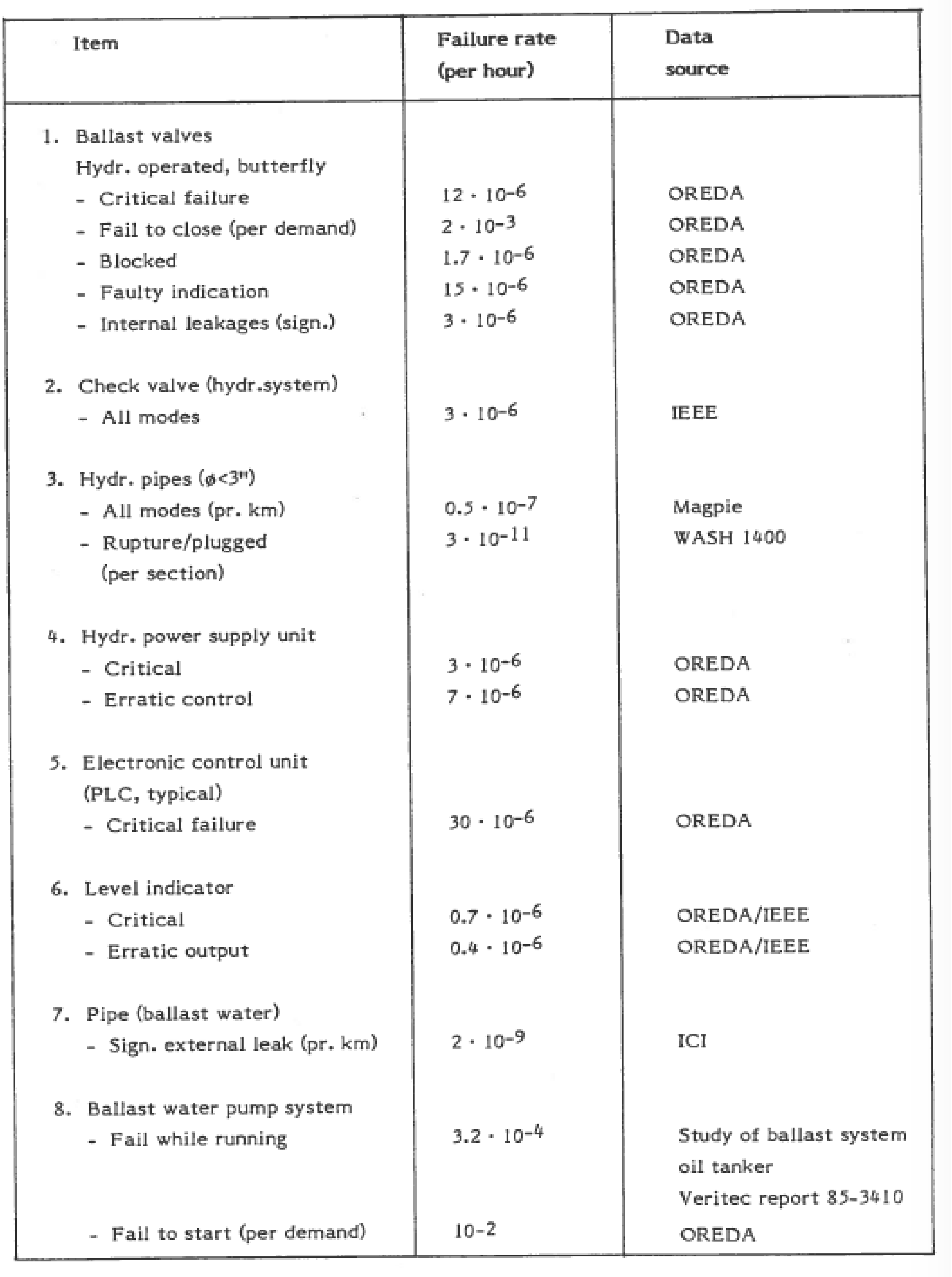
$$KG2 = \begin{pmatrix} 36 \\ 36.531 \\ 37.085 \\ 37.666 \\ 38.273 \\ 39.579 \\ 40.282 \end{pmatrix} m$$

Heeling angle $\theta_{heel} := \overrightarrow{\left(\operatorname{atan}\left(\frac{KG1 - KG2}{GM}\right)\cdot\frac{180}{\pi}\right)}$

$$\theta_{heel} = \begin{pmatrix} 0 \\ -11.564 \\ -26.047 \\ -42.234 \\ -57.734 \\ -80.575 \\ -87.97 \end{pmatrix}$$

APPENDIX C

FAILURE MODE AND EFFECT ANALYSIS & FAULT TREE ANALYSIS



Item	Failure rate (per hour)	Data source
1. Ballast valves		
Hydr. operated, butterfly		
- Critical failure	$12 \cdot 10^{-6}$	OREDA
- Fail to close (per demand)	$2 \cdot 10^{-3}$	OREDA
- Blocked	$1.7 \cdot 10^{-6}$	OREDA
- Faulty indication	$15 \cdot 10^{-6}$	OREDA
- Internal leakages (sign.)	$3 \cdot 10^{-6}$	OREDA
2. Check valve (hydr.system)		
- All modes	$3 \cdot 10^{-6}$	IEEE
3. Hydr. pipes (ø<3")		
- All modes (pr. km)	$0.5 \cdot 10^{-7}$	Magpie
- Rupture/plugged (per section)	$3 \cdot 10^{-11}$	WASH 1400
4. Hydr. power supply unit		
- Critical	$3 \cdot 10^{-6}$	OREDA
- Erratic control	$7 \cdot 10^{-6}$	OREDA
5. Electronic control unit (PLC, typical)		
- Critical failure	$30 \cdot 10^{-6}$	OREDA
6. Level indicator		
- Critical	$0.7 \cdot 10^{-6}$	OREDA/IEEE
- Erratic output	$0.4 \cdot 10^{-6}$	OREDA/IEEE
7. Pipe (ballast water)		
- Sign. external leak (pr. km)	$2 \cdot 10^{-9}$	ICI
8. Ballast water pump system		
- Fail while running	$3.2 \cdot 10^{-4}$	Study of ballast system oil tanker Veritec report 85-3410
- Fail to start (per demand)	10-2	OREDA

Figure C-1 Failure rates of ballast system components Source; Østby,., and Festøy, . (1987)

Table C- 1: Severity rate

Severity (S)		
Effects	**Evaluation**	**Ranking**
Very High Hazardous effects	Very high HSE/Production/Cost	5
High High impact	High HSE/Production/Cost	4
Moderate Moderae effects	Moderate HSE/Production/Cost	3
Low Low impact, almost negligible	Low HSE/Production/Cost	2
Very Low Negligible effect	Negligible HSE/Production/Cost	1

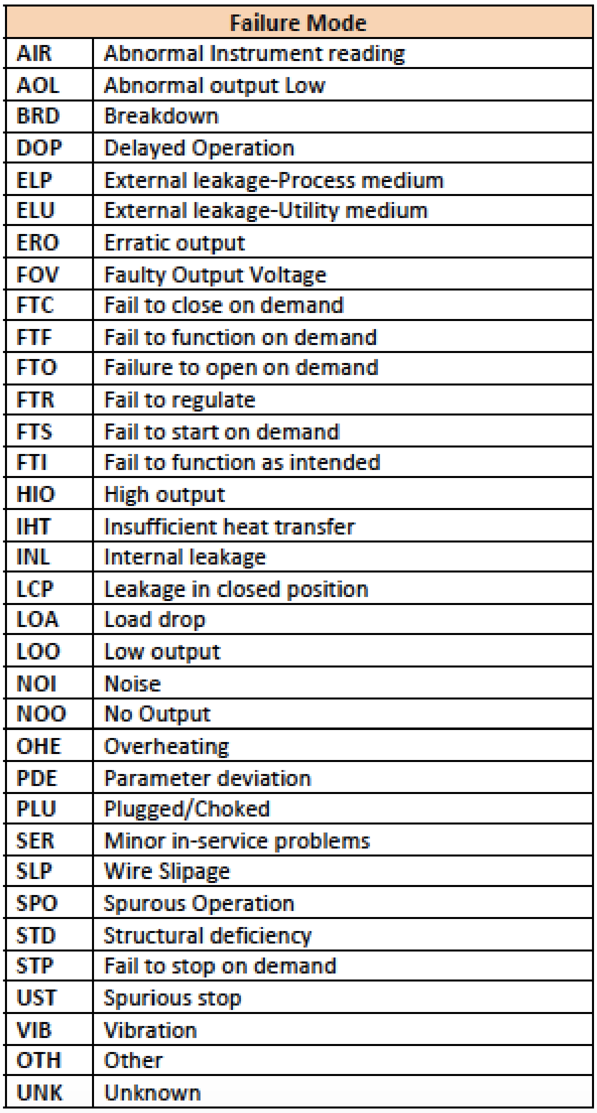
Table C- 2:Occurrence rate

Occurrence (O)		
Probability of Failure	**Avaibility**	**Ranking**
Very High Failure is almost inevitable	< 50%	5
High Failure is most likely to occur	50-70%	4
Moderate Failure is likely to occur	70-80% 70-80%	3
Low Very low chances that Failure will occur	80-90%	2
Very Low Failusre is unlikely to occur	>95%	1

Table C-3: Detection rate

Detection (D)		
Detection	**Criteria:Likelihoof of detection by Design Control**	**Ranking**
Very High	Very high chance the Design Control will detect a potential cause and subsequent failure mode	5
High	High chance the Design Control will detect a potential cause and subsequent failure mode	4
Moderate	Moderate chance the Design Control will detect a potential cause and subsequent failure mode	3
Low	Low chance the Design Control will detect a potential cause and subsequent failure mode	2
Very Low	Almost no chance the Design Control will detect a potential cause and subsequent failure mode	1

Table C- 2: Failure Mode



Failure Mode	
AIR	Abnormal Instrument reading
AOL	Abnormal output Low
BRD	Breakdown
DOP	Delayed Operation
ELP	External leakage-Process medium
ELU	External leakage-Utility medium
ERO	Erratic output
FOV	Faulty Output Voltage
FTC	Fail to close on demand
FTF	Fail to function on demand
FTO	Failure to open on demand
FTR	Fail to regulate
FTS	Fail to start on demand
FTI	Fail to function as intended
HIO	High output
IHT	Insufficient heat transfer
INL	Internal leakage
LCP	Leakage in closed position
LOA	Load drop
LOO	Low output
NOI	Noise
NOO	No Output
OHE	Overheating
PDE	Parameter deviation
PLU	Plugged/Choked
SER	Minor in-service problems
SLP	Wire Slipage
SPO	Spurous Operation
STD	Structural deficiency
STP	Fail to stop on demand
UST	Spurious stop
VIB	Vibration
OTH	Other
UNK	Unknown

	B	C	D	E	F	G	H	I	J	K	L	N	O	P	Q	R
5	**APENDIX C-2 - Failure Modes Effects Analysis (FMEA)**															
6	**Product Name:**	Ballast system					**FMEA Workshop Participants** Ihuaku Nneoma Kelechi Unegbu				**Prepared by:**		Rev.	00		
7	**Owner:**	UIS MASTER THESIS									**FMEA Date (Orig):**					
8																
9	**Main Functions**	**Potential Failure Mode**	**Local Failure Effects**	**Global Failure effects**	**SEV (S)**	**Potential Causes**	**OCCURENCE (O)**	**Current Controls**	**DETECTION (D)**	**RPN**	**Actions Recommended**	**Actions Taken**	**S E V**	**O C C**	**D E T**	**R P N**
10	**What are the functions?**	**In what ways can the function fail?**	**What is the impact of the function failure on system element/function under consideration**	**What is the impact of the function failure on system, related system, process, product, service, costumer or regulation**	**How Severe is the effect?**	**What causes the function to fail?**	**How often does cause or FM occur?**	**What are the existing controls and procedures that prevent either the Cause or the Failure Mode?**	**How well can you detect the Cause or the Failure?**	**S*O*D**	**What are the actions for reducing the occurrence of the cause, or improving detection?**	**Note the actions taken. Include dates of completion.**				
11	**BALLAST TANK COMPARTMENT**															
13	**1.Ballast tanks** are in general placed in the lower hull and columns, and symmetrical within each hull. The reason for the symmetric distribution is to be able to distribute loads evenly, to avoid shear forces and bending moments to build up, and also to be able to trim the vessel evenly. A ballast tank is a compartment within the semi floating structure that holds water,it is used as ballast to provide stability for a vessel.	**ELU**	Low pumping output due to leakage of the utilities tools such as valve	platform ballasting failure	4	Cavitation/corrosion	2	The operation and Client maintenance procedure contained in the ballasting/deballasting manual should be strictly adhere to. Daily inspection should be performed	2	16	Periodic Checking before operation for being free by turning shaft		4	2	2	16
14			failure due to pressure and parameter deviation of other ballast tanks components	platform deballasting failure	4		2		2	16			4	2	2	16
15		**INL**	excessive reduction ballast in the tanks	High heeling of the platform	3	material Failure	4		5	60	Regular checking of the components, before operation, Operates based on the manual, Regular cleaning		3	4	5	60
16			Flooding of adjacent tanks	platform instability	3		3		5	45			3	3	5	45
17		**STD**	Fatique damage of ballast compactments	Global structural failure of the platform	5	sloshing of ballast, material failure and corrosion of connection	1		3	15	periodic structural check and regular maintenance		5	1	3	15
18			Failure of plates connection of ballast tanks	Global structural failure of the platform	5		1		3	15			5	1	3	15
19	**PIPES**															
20	**2.PIPING** it's a metallic tubular pipe system(suction or delivery) used for conducting or transferring of fluid like water, oil and fuel.	**ELP**	No/low flow ballast movement due to leakage	reduced ballasting/deballasting operation	4	burst/corrosion of pipe	2	The operation and Client maintenance procedure contained in the ballasting/deballasting manual should be strictly adhere to. Daily inspection should be performed	1	8	Regular checking of the components, before operation, Operates based on the manual, Regular cleaning		4	2	1	8
21			-	make redundant other related system	4		2		1	8			4	2	1	8
22		**SER**	No/low flow ballast movement due to leakage	reduced ballasting/deballasting operation	4	Leakage/erosion	1		1	4	Regular checking of the components, before operation, Operates based on the manual, Regular cleaning		4	1	1	4
23			Cause overheating of some parts seals due to inappropriate flow	under ultilization of related system and proscess	4		1		1	4			4	1	1	4
24		**VIB**	No transportation of fluid due to structural failure	reduced ballasting/deballasting operation	4	Fatigue	2		4	32	adequate structural support provided and vibration damping components installed		4	2	4	32
25			make redundant other system elements	make redundant other related system	4		2		5	40			4	2	5	40
26		**STD**	Fatique damage to other attached system elements	No ballasting/deballasting operation	4	Erosion/excessive deformation/excessive vibration	2		2	16	periodic structural check and regular maintenance		4	2	2	16
27			Vibration of other connected components attached	damage to other related components	2		4		4	32			2	4	4	32
28	**ELECTRIC POWER SYSTEM**															
29	**3.Main Power Supply Generator;** Electric power is mainly used for ballast control system, pumps and hydraulic units. A power supply is an electronic device that supplies electric energy to an electrical load. The primary function of a power supply is to convert one form of electrical energy to and, as a result, power supplies are sometimes referred to as electric power converters	**BRD**	Generator Failure and main electric supply unavailable	loss of main electric power supply to the ballasting/deballastion control system operation	3	Generator Failure	2	The operation and Client maintenance procedure contained in the ballasting/deballasting manual should be strictly adhere to. Daily inspection should be performed	4	24	regular inspection and maintenace		3	2	4	24
30		**ERO**	Damage to components that utilises electricity due to flunctuating power supply	halting of ballast operation	4	Faulty Generator	2		4	32	regular inspection and maintenace		4	2	4	32
31			Damage to ballast control system components	Delay in ballasting operation	3		2		4	24			3	2	4	24
32		**UST**	Unavailability of main electric power supply	loss of main electric power supply during ballasting and deballastion operation	2	Generator Control Failure	1		5	10	Regular checking of the components, before operation, Operates based on the manual		2	1	5	10
33			Damage to ballast control system components	Delay in ballasting and deballasting operation	4		1		3	12			4	1	3	12
34		**HIO**	excessive main power supply and damage to ballast control system	loss of main electric power supply during ballasting and deballastion operation	3	Faulty Generator	2		4	24	Regular checking of the components, before operation, Operates based on the manual		3	2	4	24
35		**LOO**	Inadequate main power supply and damage to ballast control system	halting of ballast/deballasting operation	2	Faulty Generator	2		3	12	Regular checking of the components, before operation, Operates based on the manual.		2	2	3	12
36		**FTS**	Unavailability of main electric power supply	Delay in ballasting/deballasting operation	2	Generator Control Failure	2		4	16	Regular checking of the components, before operation, Operates based on the manual		2	2	4	16
37			-	downtime for the ballasting/deballasting operation	2		2		5	20			2	2	5	20
38	**4.Emergency Backup Generator** An emergency power system is an independent source of electrical power that supports important electrical systems on loss of normal power supply. A standby generator is a back-up electrical system that operates automatically.[1] Within seconds of a utility outage an automatic transfer switch senses the power loss, commands the generator to start and then transfers the electrical load to the generator	**BRD**	Generator Failure and main electric supply unavailable	loss of backup electric power supply during ballasting/deballastion operation	5	backup generator failure	1	The operation and Client maintenance procedure contained in the ballasting/deballasting manual should be strictly adhere to. Daily inspection should be performed	5	25	application of suitable oil should be encouraged and Regular maintenance of cooling system		5	1	5	25
39		**ERO**	Damage to components that utilises electrical fauire due to flunctuating power supply	halting of ballast operation	5	Faulty backup generator	1		2	10	application of suitable oil should be encouraged and Regular maintenance of cooling system		5	1	2	10
40			Backup generator control Failure	Delay in ballasting operation	5		1		2	10			5	1	2	10
41		**UST**	Unavailability of main electric power supply	loss of main electric power supply during ballasting and deballastion operation	5	Backup generator Control Failure	1		5	25	application of suitable oil should be encouraged and Regular maintenance of cooling system		5	1	5	25
42			Damage to utility Components in the event of failure of main power supply	Delay in ballasting and deballasting operation	4		1		5	20			4	1	5	20
43		**HIO**	Damage to utility Components in the event of failure of main power supply	loss of main electric power supply during ballasting and deballastion operation	4	Faulty backup generator	1		2	8	Regular checking of the components, before operation, Operates based on the manual		4	1	2	8
44		**LOO**	Inadequate backup electric power supply	no electric power supply backup for ballasting/deballasting operation	4	Faulty backup generator	1		4	16	Regular checking of the components, before operation, Operates based on the manual		4	1	4	16
45		**FTS**	Unavailability of backup electric power supply	Delay in ballasting operation in the event of failure of main electric power supply	5	Backup generator control failure	1		4	20	Regular checking of the components, before operation, Operates based on the manual		5	1	4	20
46	**5.Uninterrupted Power Supply (UPS)** The UPS is intended to supply electricity in the mean time in the occasion where the main power does not supply electricity, until the backup generator is running	**BRD**	unavailability of temporary backup power supply	No backup electrical power supply for ballast/deballasting control system	5	UPS failure	2	The operation and Client maintenance procedure contained in the ballasting/deballasting manual should be strictly adhere to. Daily inspection should be performed	5	50	Regular checking of the components, before operation, Operates based on the manual		5	2	5	50
47		**ERO**	Unreliable temporary backup power supply	No backup electrical power supply for ballast/deballasting control system	4	UPS failure	1		5	20	Regular checking of the components, before operation, Operates based on the manual		4	1	5	20
48		**FTS**	unavailability of temporary backup power supply	No backup electrical power supply for ballast/deballasting control system	5	UPS failure	1		5	25	Regular checking of the components, before operation, Operates based on the manual		5	1	5	25

	B	C	D	E	F	G	H	I	J	K	L	N	O	P	Q	R
49	**HYDRAULIC POWER SYSTEM**															
50	**6.Main Hydraulic Power Generator** The MHPG provides hydraulic pressurre required by the ballast system. it transforms the hydraulic power of a working system into high quality electricity with great efficiency. It also eliminates dependency on wires across troublesome areas such as electric swivels, repetitive bend joints, and lengthy wire runs	**BRD**	loss of main hydraulic pressure function	halting ballasting and deballasting operation due to loss of hydraulic power	5	Hydraulic pump failure	1	The operation and Client maintenance procedure contained in the ballasting/deballasting manual should be strictly adhere to. Daily inspection should be performed	5	25	Regular checking of the components, before operation, Operates based on the manual		5	1	5	25
51		**DOP**	temporary unavailability of main hydraulic power fuction	halting ballasting and deballasting operation due to loss of hydraulic power	2	High pressure distance	2		4	16	Regular checking of the components, before operation, Operates based on the manual		2	2	4	16
52		**ELP**	loss of hydraulic pressure	reduced ballasting/deballasting operation	2	hydraulic fluid failure	1		5	10	Regular checking of the components, before operation, Operates based on the manual		2	1	5	10
53		**FTF**	loss of hydraulic accumulator function	No ballasting/deballasting operation due to loss of hydraulic function	3	control Signal Failure	1		5	15	Regular checking of the components, before operation, Operates based on the manual		3	1	5	15
54		**UST**	Unavailability of hydraulic function	halting ballasting and deballasting operation due to loss of hydraulic power	2	control Signal Failure	3		5	30	Regular checking of the components, before operation, Operates based on the manual		2	3	5	30
55		**STP**	Damage to other components due to uncontrol hydraulic function	uncontrol ballast and deballasting operation	5	control Signal Failure	2		4	40	Regular checking of the components, before operation, Operates based on the manual		5	2	4	40
56	**7.Hydraulic Accumulators** A hydraulic accumulator is a pressure storage reservoir in which a non-compressible hydraulic fluid is held under pressure that is applied by an external source. The external source can be a spring, a raised weight, or a compressed gas. Accumulators can increase efficiency, provide smoother, more reliable operation, and store emergency power in case of electrical failure. It is a simple hydraulic device which stores energy in the form of fluid pressure	**BRD**	loss of accumulator function	halting ballasting and deballasting operation due to loss of hydraulic power	5	accumulator Failure	1	The operation and Client maintenance procedure contained in the ballasting/deballasting manual should be strictly adhere to. Daily inspection should be performed	3	15	Regular checking of the components, before operation, Operates based on the manual		5	1	3	15
57		**ELP**	temporary unavailability of hydraulic accumulator fuction	halting ballasting and deballasting operation due to loss of hydraulic power	5	structural damage	1		5	25	application of suitable oil should be encouraged and Regular maintenance of cooling system		5	1	5	25
58			loss of hydraulic pressure	reduced ballasting/deballasting operation	5		1		5	25			5	1	5	25
59		**FTF**	Unavailability of hydraulic backup power	No ballasting/deballasting due to loss of backup hydraulic function	5	accumulator Failure	1		5	25	application of suitable oil should be encouraged and Regular maintenance of cooling system		5	1	5	25
60			Unavailability of hydraulic function	halting ballasting and deballasting operation due to loss of hydraulic power	5		1		5	25			5	1	5	25
61	**BALLAST CONTROL SYSTEM**															
62	**8.Ballast Valves** Hydraulic power is used to operate ballast valves. An electrically driven pump unit called a hydraulic power unit (HPU) provides pressure to the control console that provides pressure to each actuator/valve in the system (Hancox, 1996). For emergency situations where the HPU does not function, hand pumps can be connected into the pressure side of the system to man- ually control valves. Valves include; Sea chest valves, pump room valves, discharge valves and ballast tank valves	**BRD**	No ballast valve function	Flooding or no ballasting/deballasting operation	4	Value failure/breakage	2	The operation and Client maintenance procedure contained in the ballasting/deballasting manual should be strictly adhere to. Daily inspection should be performed	5	40	Periodic Checking before operation for being free by turning shaft		4	2	5	40
63				No ballasting/deballasting due to mechanical breakdown	4		2		5	40			4	2	5	40
64		**DOP**	temporary unavailability of Valve fuction	Delayed ballasting and deballasting operations	3	Faulty feedback from valve	3		3	27	application of suitable oil should be encouraged and Regular maintenance of cooling system		3	3	3	27
65		**FTO**	ballast tank is closed	No ballasting/deballasting operation	5	Actuator Failure	2		3	30	application of suitable oil should be encouraged and		5	2	3	30
66		**FTC**	ballast tank is opened	uncontrolled ballasting/deballasting operation	5	Actuator Failure	3		4	60	Routine filter cleaning and regular inspection should be performed		5	3	4	60
67		**INL**	bidirectional ballast leakage	uncontrolled ballasting/deballasting operation	4	Valve erosion/corrosion	2		3	24	Routine filter cleaning and regular inspection should be performed		4	2	3	24
68		**STD**	Damage to other system components as a result of unregulated pressure	No production output	5	valve component failure	4		2	40	Periodic Checking before operation for being free by turning shaft		5	4	2	40
69			No ballast valve function	No/low/high production due to improper valve	5		2		3	30			5	2	3	30
70		**UST**	No ballast valve function	halting of ballasting/deballasting operation	5	Selenoid Failure	1		5	25	Regular and periodic maintenance and inspection based operation manual		5	1	5	25
71	**9.Ballast Pump** Ballast pump is used to empty or fill the heeling tank. It is designed to efficiently transfer vast amount of sea water into the marine vessels	**BRD**	Damage to other system elements due to unregulated flow.	Low/High production due to mechanical breakdown	4	Pump Motor Failure	1	The operation and Client maintenance procedure contained in the ballasting/deballasting manual should be strictly adhere to. Daily inspection should be performed	5	20	Regular and periodic maintenance and inspection based operation manual		4	1	5	20
72			No pumping	No ballasting/deballasting due to loss of pumping function	5		2		5	50			5	2	5	50
73		**DOP**	temporary unavailability of pump fuction	Delayed ballasting and deballasting operations	5	No Control Signal	2		2	20	Routine inspection and maintenance, Routine cleaning, Scale & corrosion inhibitor, coating		5	2	2	20
74		**FTR**	pumping stop	Cause overheating or mechanical damage to some parts like bearings due to no/low flow	5	No Control Signal	1		5	25	application of suitable oil should be encouraged and Regular maintenance of cooling system		5	1	5	25
75			Damage to other components due to variation in flow input or output	uncontroled ballast and deballasting operation	3		1		5	15			3	1	5	15
76		**STP**	Damage to other components due to uncontrol flow such as valve	uncontroled ballast and deballasting operation	3	Pump Motor Failure	2		5	30	Routine inspection and maintenance, Routine cleaning, Scale & corrosion inhibitor, coating		3	2	5	30
77		**STD**	Damage to other system components as a result of unregulated pressure	Delay in ballasting and deballasting operation	4	Pump Motor Failure	1		1	4	Regular and periodic maintenance and inspection based operation manual		4	1	1	4
78			Loss of pump functions	No/low/high production due to improper valve	4		2		5	40			4	2	5	40
79		**FTS**	Unavailability of pump function	delay in ballasting and deballasting operation, thus semi rig stability problematics	2	Faulty pump motor	5		5	50	Regular and periodic maintenance and inspection based operation manual				5	50
80			unwarranted damage to other system elements due to false stop	loss of ballasting and deballasting operation	5	Pump Motor Failure	1		4	20	Routine inspection and maintenance, Routine cleaning, Scale & corrosion inhibitor, coating		5	1	4	20
81	**10.Ballast Control Logic unit** this system provides electrical control signal, it controls the ballasting and de-ballasting operation by responding to commands from the operator and it also acts on its own to perform automated tasks.	**AIR**	Loss of Control Valves and pump functions	Loss of valve and pump control	5	Faulty feedback from valve and pump	1	The operation and Client maintenance procedure contained in the ballasting/deballasting manual should be strictly adhere to. Daily inspection should be performed	2	10	Routine inspection and maintenance, Routine cleaning, Scale & corrosion inhibitor, coating		5	1	2	10
82			Low/high pumping due to false/real high/low signal	Improper ballasting and deballasting operation	4		1		1	4			4	1	1	4
83		**BRD**	Loss of Control Valves and pump functions	Delay in ballasting and deballasting operation	5	control Logic Failure	1		1	5	application of suitable oil should be encouraged and Regular maintenance of cooling system		5	1	1	5
84			Unavailability of control signal	Inaccurate ballasting and deballasting Operation	5		1		1	5			5	1	1	5
85		**PDE**	Damage to other components due to parameter deviation	Delay in ballasting and deballasting operation	5	Faulty feedback from valve and pump	1		1	5	Routine inspection and maintenance, Routine cleaning, Scale & corrosion inhibitor, coating		5	1	1	5
86			Cause improper operation for some members like valves due to false readings		5		2		1	10			5	2	1	10
87		**UST**	unwarranted damage to other system elements due to false stop	halting of ballast and deballasting operation	5	control Logic Failure	2		1	10	Regular and periodic maintenance and inspection based operation manual		5	2	1	10
88		**FTI**	Loss of Control Valves and pump functions	Loss of valve and pump control	4	Faulty feedback from valve and pump	1		1	4	Routine calibration of pressure transmitter, Routine inspection and maintenance		4	1	1	4
89			Uncontroled Value and pump operation	Improper ballasting and deballasting operation	5		1		2	10			5	1	2	10
90		**FTR**	Uncontroled Value and pump operation	Improper ballasting and deballasting operation	4	control Logic Failure	1		2	8	Regular and periodic maintenance and inspection based operation manual		4	1	2	8

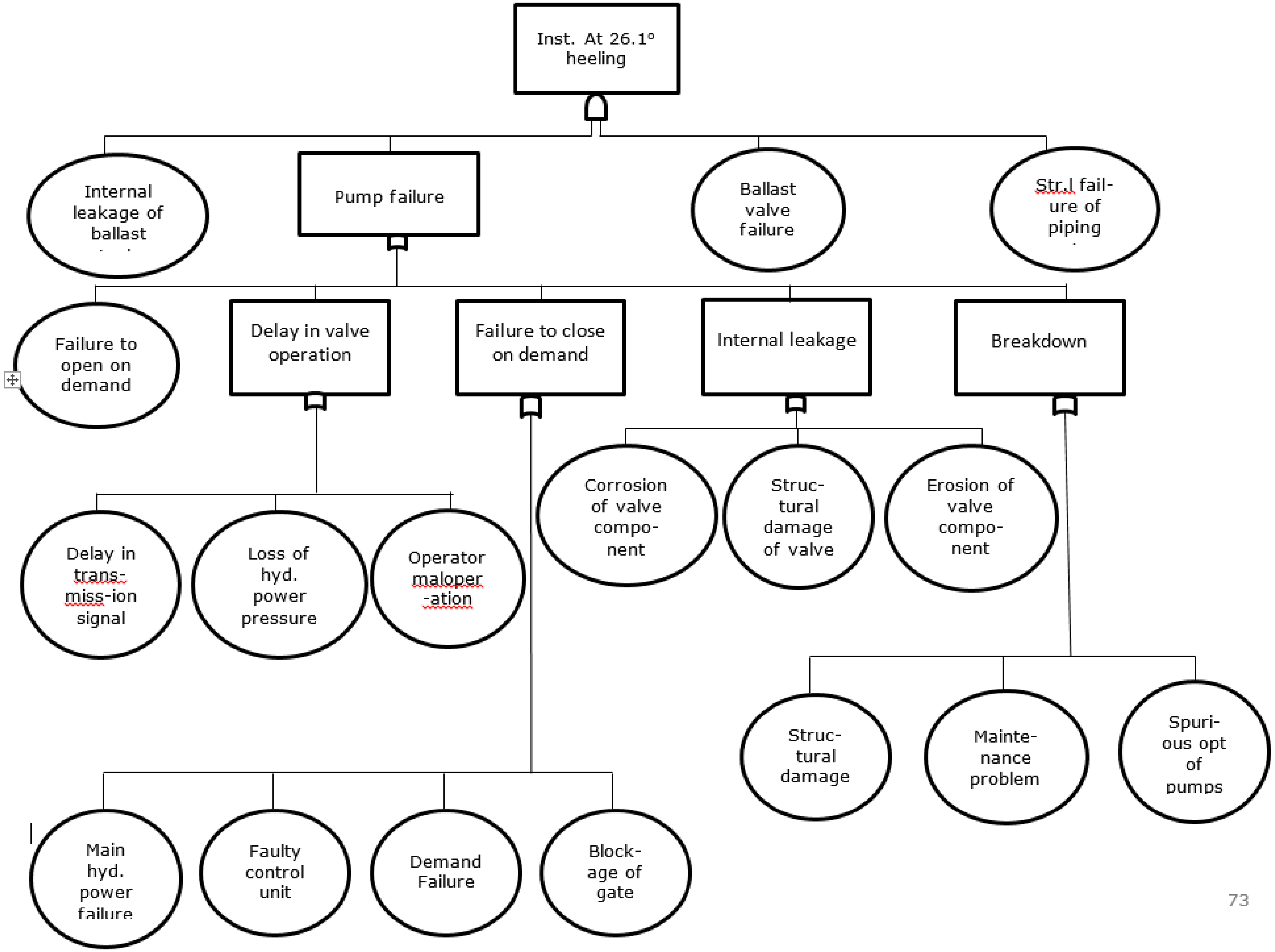


Figure C- 3; Fault Tree analysis

APPENDIX D-1

BARRIER DIAGRAMS AND BARRIER ANALYSIS

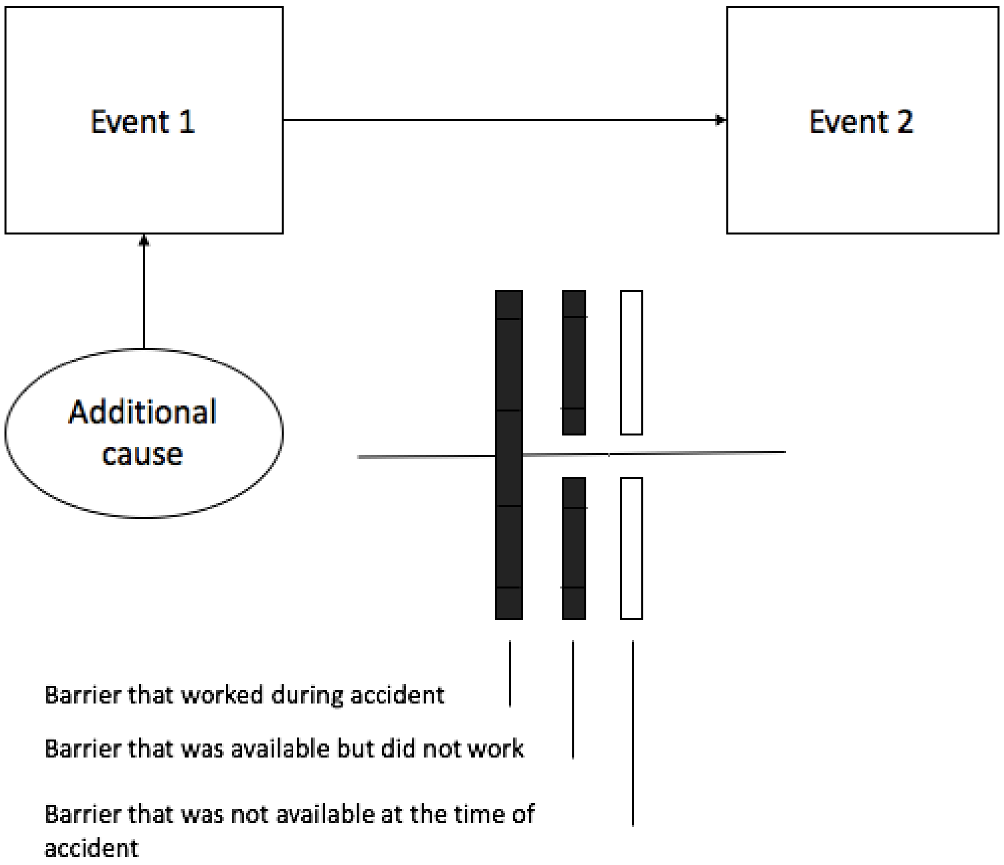


Figure D- 1; description of the nodes in the barrier diagram

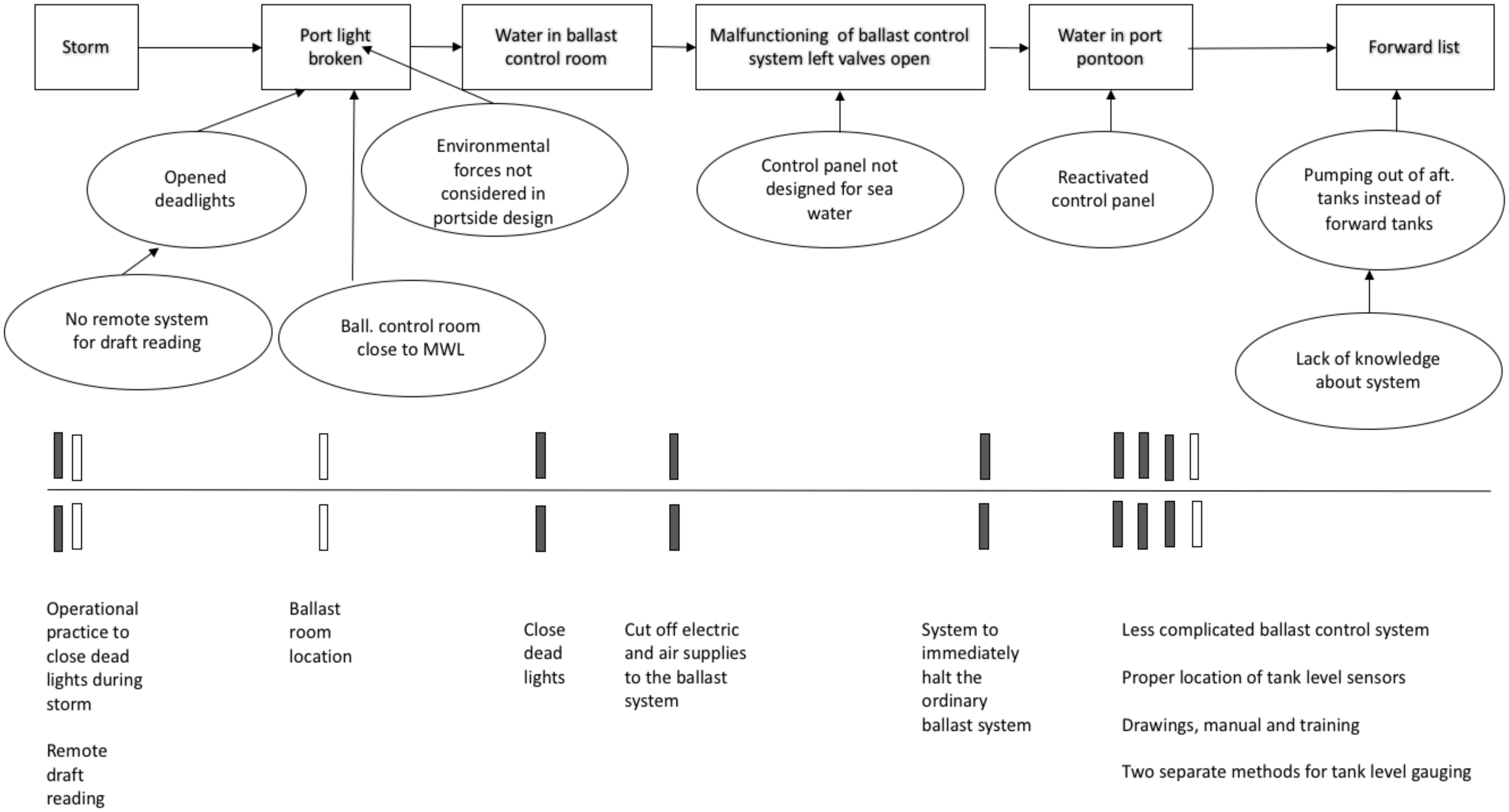


***Figure D- 2*: Ocean ranger (1982)**

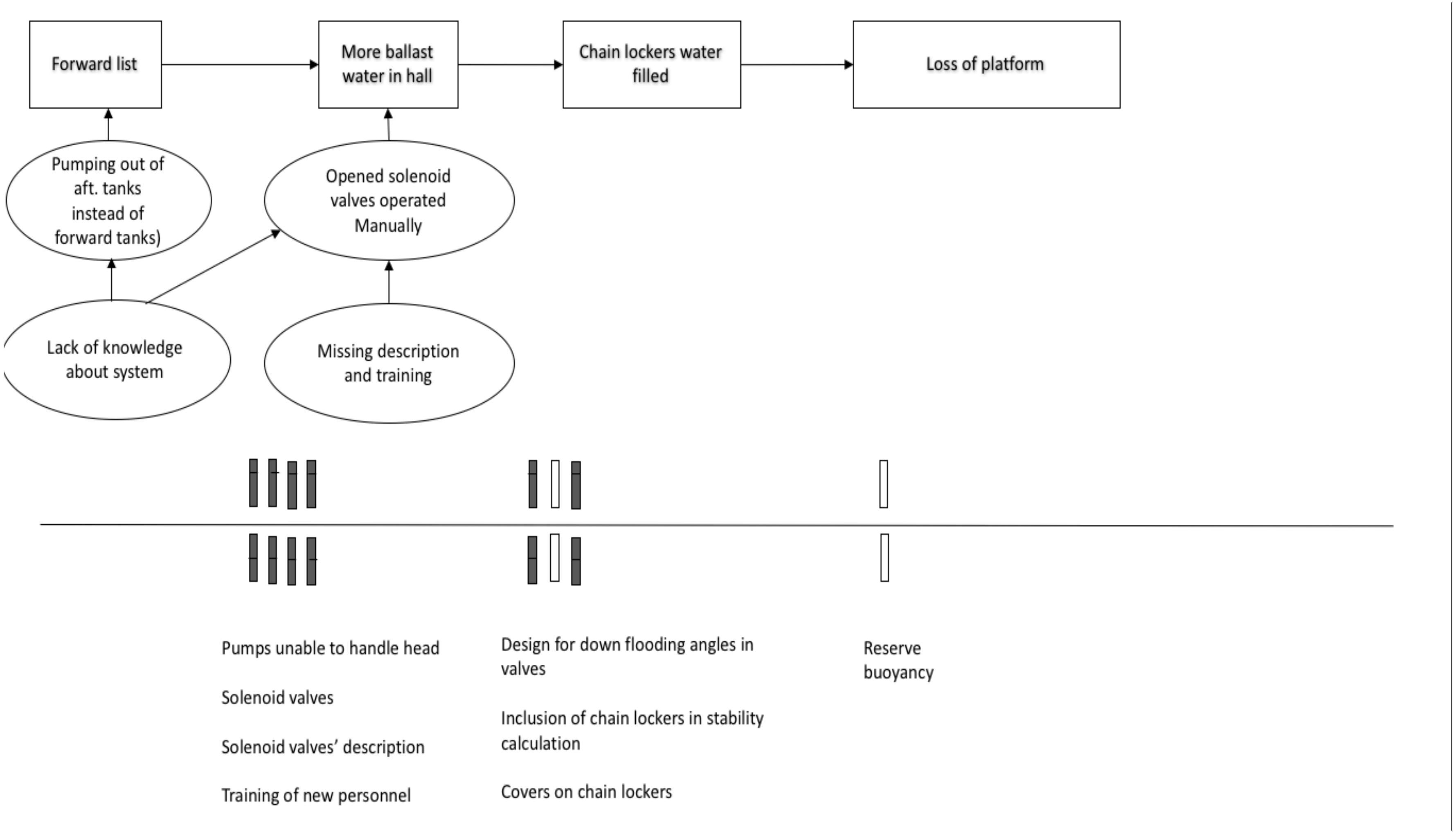


Figure D- 3; **Ocean ranger (1982) (Contd.)**

Performance colour codes

Red = Barrier failure
Yellow = Partial barrier failure

Green = Barrier success

Glossary

HMI = Human Machine Interference
PTW = Permit to work system
N/A = Not Applicable

Table D- 3: Ocean Ranger accident barrier performance table. Source; COWI, (2003); Vinnem (2013)

Barrier functions	**Barrier System**	**Barrier Element**			**Risk Influencing Factors**	**Barrier Performance**
		Technical	Operational	Organisational		
🟥 **A. Maintain Structural Integrity and Marine Control**	1. Ballast Control System	-Ballast control room -Remote system -Control panel - deadlights -Alarms	- Monitor system - Alarm response	- Operator	-Response time - Decision making training -Competence - HMI	**FAILURE OF BARRIER** The control room was vulnerable to bad weather due to its location. It was close to the mean water level (i.e., in a column. This caused a portlight to break as a large wave appeared.
	2. Operations and Maintenance	-Maintenance standards	-Maintenance manual	-Shift workers - Shift manager -Supervisor	- Safety culture -Inspection - Quality procedures - supervision	The remote system was not in place to read the draft of the rig, resulting to open deadlights
	3. Design Safety and weathertight integrity	- Industrial standards - Doors - Hatchways - Machinery space openings - Ventilators - Air pipes - Inlets and discharges - Freeing ports	-Testing -Quality audits -Position definition	- Design team	-Safety critical expertise - Safety culture -Design procedure -Technical condition -Industrial standard conformance	Insufficiently robust design of the components in the control panel. They were not designed to be protected against sea water The management did not make training programs and operational manuals available to the

						personnel. This is therefore the reason why the two operators on duty lacked familiarity and expertise to close the deadlights during the storm
B. prevent escalation of initiating failure	- Ballast control console	-Emergency detectors -Alarms -Detect leakage - ballast valve actuators -Sensor tube	-Respond to detectors - Swift response to alarms	-Operator -Platform Manager	- Communication - Condition of tech. systems - Operating procedures -Experience -Work practice - Weather -Response time -Action criteria -Design robustness -Emergency response training	**FAILURE OF BARRIER** The ballast control console was susceptible to common faults and confusing information. This was due to the interconnection between the electrical circuits used for control and monitoring aspects There was imprecision in the tank level gauge as a result of location of the sensors The forward tanks were not functioning as needed due to low capacity of the pumps
	-Pumping and draining system	-Communication systems -Pumps -Emergency drain tanks	- Pumping and draining drills	-Operator		
	- Emergency Shutdown system	-Emergency detectors -Alarms -Emergency cut off electricity and air supplies to ballast system	-Respond to detectors - Swift response to alarms	-Emergency support vessel crew -Platform Manager		

C. prevent total loss	1. Additional ballast back up system	- ballast valve actuators -Backup sensors -Control panel -Pump room valves -Ballast valves -Sea chest valves -Discharge valves -Ballast pumps -Alarms -Chain Lockers	- Monitor sensors -Control valves	- Operator -Platform Manager	- Safety culture -Design procedure -Technical condition -Response time -Action criteria	**FAILURE OF BARRIER** There was no available installed alarm system in place to alert the crew of the impending flooding of the chain lockers The pumps were inefficient as they were not able to move water around when the rig was subjected to a 6 degrees list
	2. Water tight integrity	-Watertight doors -Bulkhead valves -Bilge system	-Condition monitoring	-Operator -Platform Manager	-Design robustness Design procedure	Although the regulation required certain integrity and buoyancy of the upper hull structure, it was not implemented in the design The Chain lockers were susceptible to flooding through its pipe and wire trunk openings on top of the corner columns. this resulted to loss of buoyance, hence the capsize of the platform.
D. Prevent fatalities	1. Evacuation system	- Evacuation routes - Safety devices - Muster area	-Alarm response by personnel - Rescue operations - Evacuation vessel contact	- Emergency response team - Rescue teams - Platform manager	- Leadership - safety equipment accessibility - Competence - Evacuation training - Response timing - Reporting - Decision making ability	**FAILURE OF BARRIER** Some of the safety boats were unavailable because of presence of trim. This was due to the fact that procedure was in place for standby boats during the storm.

🟥	2. Communication system	- Alarm - Public address system - other communication channels	- Internal communication - External communication	- Operator - Platform manager	- Communication - Weather -Communication channels - Instruction clarity -Response timing	The SAR rescue helicopters were vulnerable to bad weather hence, not able to be deployed Communication was ineffective hence, complications in the search and rescue preparedness

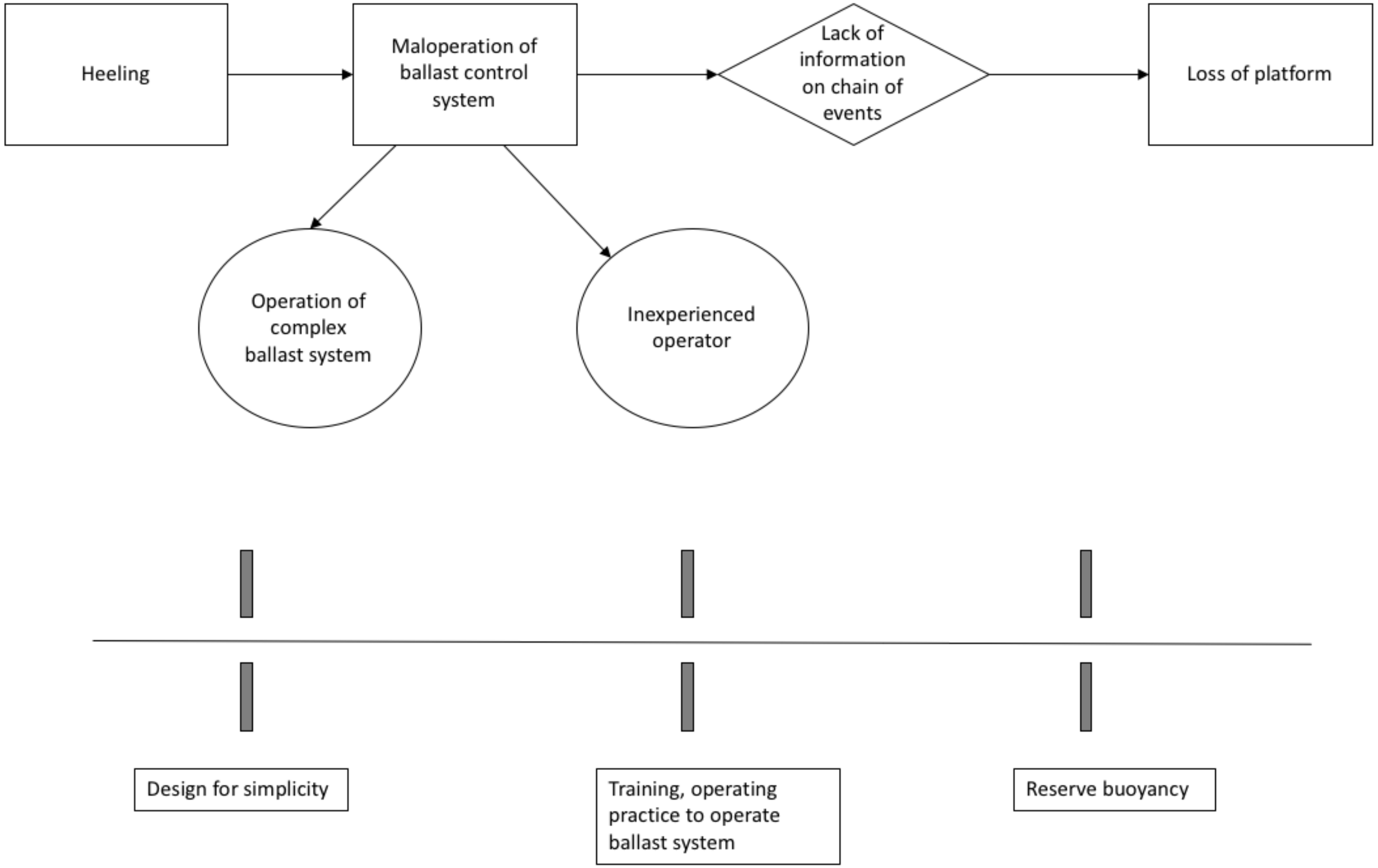


Figure D- 4; Ocean Developer (1995)

Performance colour codes

Red = Barrier failure
Yellow = Partial barrier failure
Green = Barrier success

Glossary/Acronyms

HMI = Human Machine Interference
EDT = Emergency drain tank
N/A = Not Applicable
FUP =Sole Petroleum Workers Federation

Table D- 4; Possible barrier performance table for Ocean Developer Source; COWI, (2003). Vinnem, (2006)

Barrier functions	**Barrier System**	**Barrier Element**			**Risk Influencing Factors**	**Barrier Performance**
		Technical	Operational	Organisational		
A. Maintain Structural Integrity and Marine Control	1. Ballast Control System	-Ballast control room -Remote system -Control panel - deadlights -Alarms	- Monitor system - Alarm response	- Operators	-Response time - Decision making training -Competence - (HMI)	**FAILURE OF BARRIER** The overall ballast system was complex, hence vulnerable to human error. This resulted to someone pushing the wrong button
	2. Design Safety	- Industrial standards	-Design Team -Quality audits	- Design team	-Safety critical expertise - Safety culture -Design procedure -Technical condition -Industrial standard conformance	
B. Prevent escalation of initiating failure	**Lack of Information**	**Lack of Information**	**Lack of Information**	**Lack of Information**	**Lack of Information**	**Lack of Information**

C. Prevent total loss	**Lack of Information**	**Lack of Information**	**Lack of Information**	**Lack of Information**	**Lack of Information**	**Lack of Information**
D. Prevent fatalities	1 Evacuation system	- Evacuation routes - Safety devices - Muster area	- Alarm response by personnel - Rescue operations - Evacuation vessel contact	- Emergency response team - Rescue teams - Platform manager	- Leadership - safety equipment accessibility - Competence - Evacuation training - Response timing - Reporting - Decision making ability - Weather	**SUCCESS OF BARRIER** The emergency evacuation team was functional and effective as they made towing vessels (emergency tug boat) readily available to save 24 crew members before the rig capsized
	2 Communication system	- Alarm - Public address system - other communication channels	- Internal communication - External communication	- Operator - Platform manager	-Communication channels - Instruction clarity -Response timing	

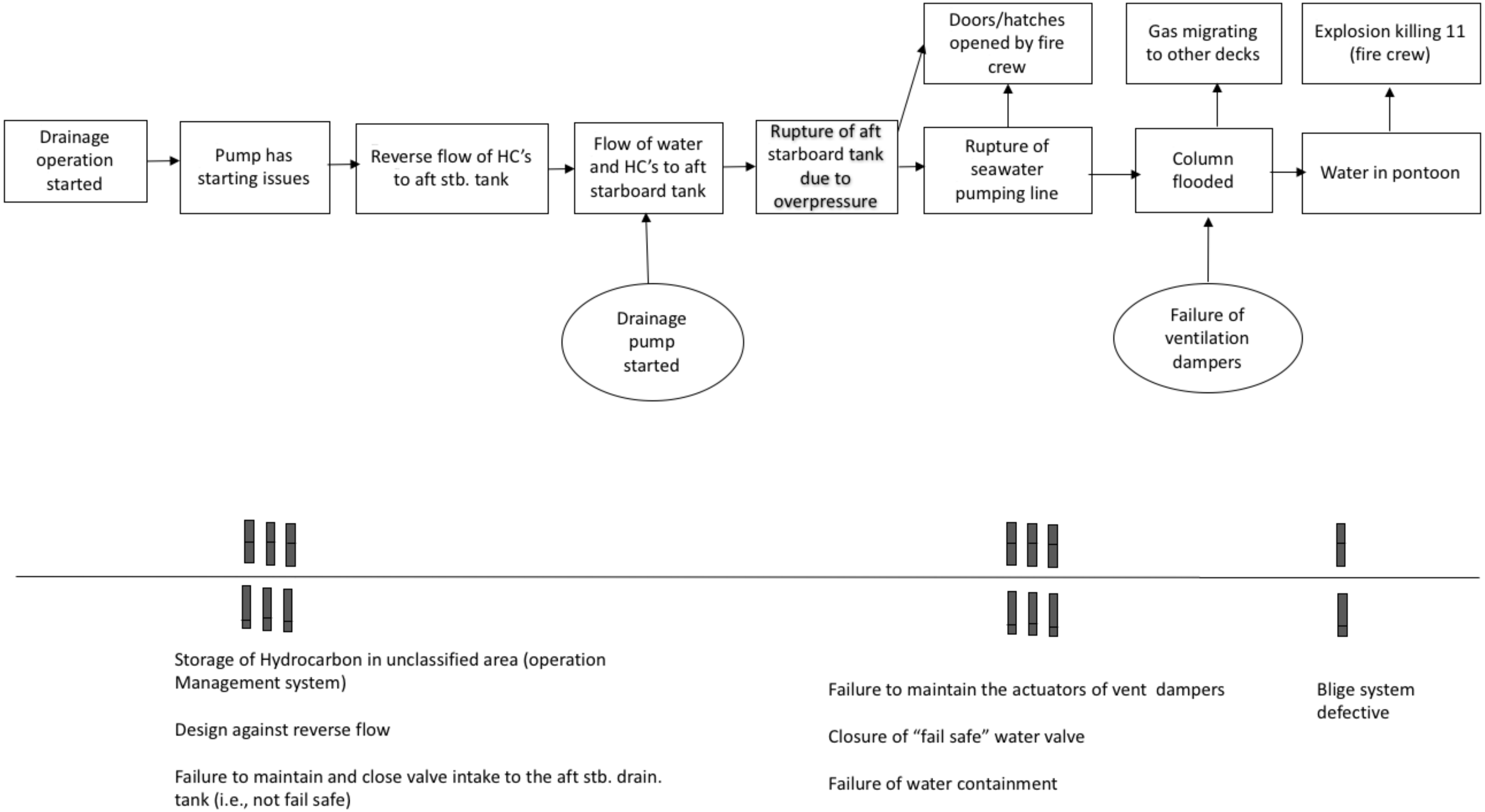


Figure D- 5: PETROBRAS P-36 (1982)

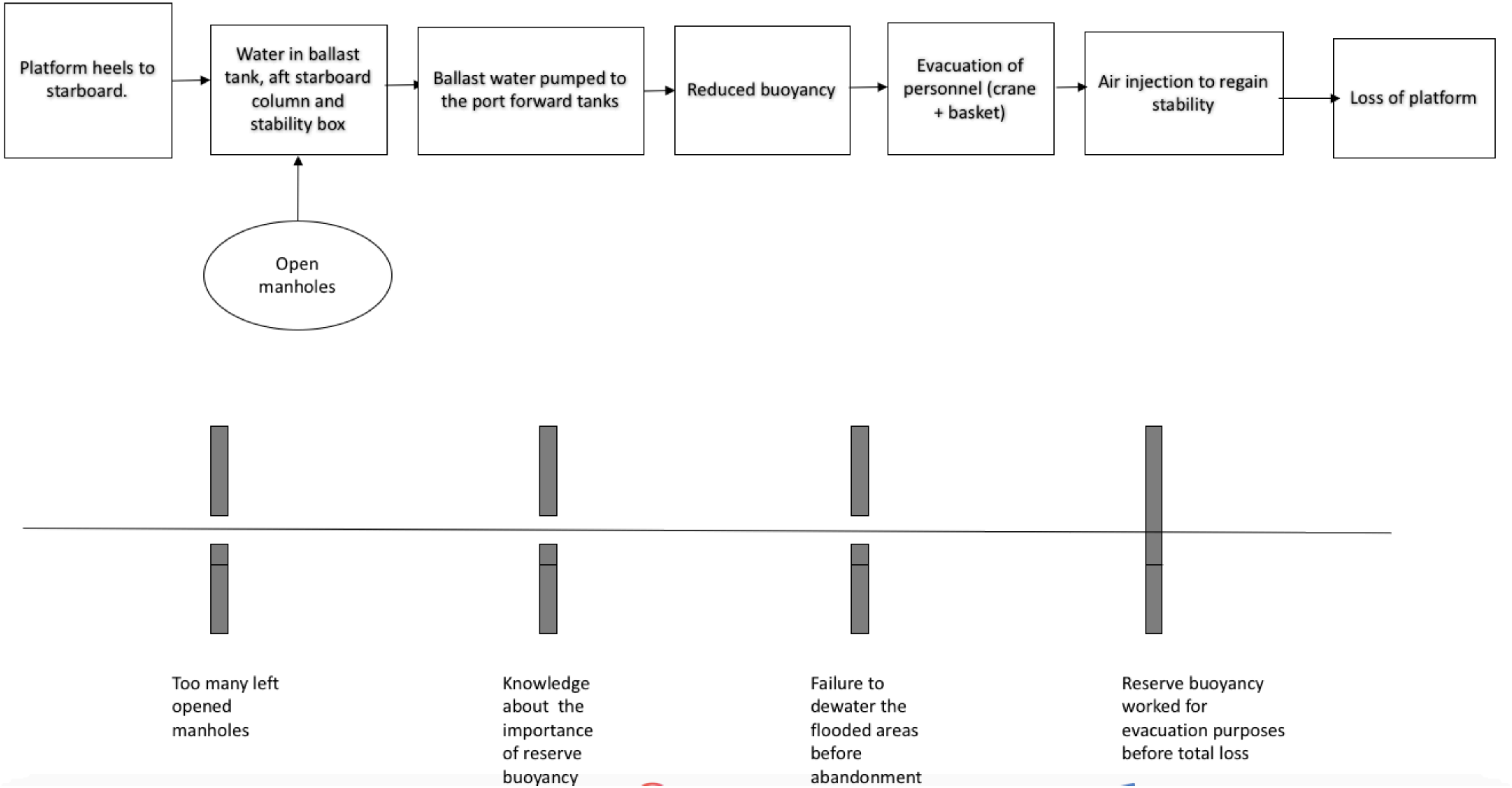


Figure D- 6; PETROBRAS P-36 (1982) (Contd.)

Performance colour codes

Red = Barrier failure
Yellow = Partial barrier failure
Green = Barrier success

Glossary/Acronyms

HMI = Human Machine Interference
EDT = Emergency drain tank
N/A = Not Applicable
FUP =Sole Petroleum Workers Federation

Table D- 5; Petrobras p-36 performance table. *Source*; COWI, (2003); Sobena, (2007); NASA, (2008)

Barrier functions	**Barrier System**	**Barrier Element**			**Risk Influencing Factors**	**Barrier Performance**
		Technical	Operational	Organisational		
A. Maintain Structural Integrity and Marine Control	1 Ballast Control System	-Ballast control room -Remote system -Emergency drain tanks -Control panel - deadlights -Alarms	- Operator	- Monitor system - Alarm response	-Response time - Decision making training -Competence - HMI	**FAILURE OF BARRIER** The right side starboard EDT was removed for repair. However, the port left side EDT was left for operation which when activated allowed buildup of water, oil and gas in pipes connecting both EDTs The Valve was leaking and allowed a mixture of fluids and vapour into the starboard EDT which made tank vulnerable to According to the Sole Petroleum Workers Federation (FUP), the decision to reduce workforce was an underlying cause of the disaster. Over a decade earlier, workers were
	3. Operations and Maintenance	-Maintenance standards	-Maintenance manual -	-Shift workers - Shift manager -Supervisor	- Safety culture -Inspection - Quality procedures - supervision	

						reduced and outsourced to subcontractors with little or no training
B. Prevent escalation of initiating failure	1 Ballast control console	Emergency detectors -Alarms -Detect leakage - ballast valve actuators -Sensor tube	-Respond to detectors - Swift response to alarms	-Operator -Platform Manager	- Communication - Condition of tech. systems - Operating procedures - Experience - Work practice -Response time -Action criteria -Design robustness -Design robustness -Emergency response training -Communication channels - Instruction clarity -Response timing	**FAILURE OF BARRIER** Lack of expertise in the part of operators was highlighted as they failed to follow procedures to prevent flooding after they opened the stability box and ballast tank for inspection. The ballast control console was vulnerable to confusing information and faults. This was due to interconnection between the electrical circuits. The electrical circuits were used for monitoring and control aspects Ventilation damper's actuators failed due to poor maintenance. The fire brigade actions and ventilation ducts which opened the water tight doors allowed the flow of gas to an ignition source thereby causing an explosion. This led to the death of 11 personnel Failure to prioritize alarm entries. About 1,723 alarms rang in the space of 17 minutes between the EDT rupture and the explosion. This could have been overwhelming to the operators thereby subjecting them under stress.
	2 Pumping and draining system	-Communication systems -Pumps -Emergency drain tanks	- Pumping and draining drills	-Operator		
	3. Water tight integrity	Watertight doors -Bulkhead valves -Blast protection doors	-Condition monitoring	-Operator		
	4. Emergency Shutdown system	-Emergency detectors -Alarms -Emergency cut off electricity and air supplies to ballast system	-Respond to detectors - Swift response to alarms	-Emergency support vessel crew -Platform Manager		
	5. Communication system	-Alarm - Public address system - other communication channels	- Internal communication -External communication	-Operator -Platform manager		

						The public address system failed to function. This resulted to a communication gap between operators and the public address team , as they were not informed about a ruptured pipe flooding into the column
C. prevent total loss	1. Flood control system (Reserve buoyancy)	- Ballast valve actuators -Sensor tube -Control panel -Pump room valves -Ballast valves -Sea chest valves -Discharge valves -Ballast pumps -Buoyance reserve	- Operator -Platform Manager	- Operator -Platform Manager	- Safety culture -Design procedure -Technical condition Response time -Action criteria -Cost cutting	**FAILURE OF BARRIER** Failure by design engineer to implementation the design of integrity and buoyancy for upper hull structures as required by regulations The sensor tube's location for tank level gauges were not precise in tilted condition. This made it difficult to read hence losing its functionality
	2. Water tight integrity	-Watertight doors -Bulkhead valves -Bilge system	-Condition monitoring	-Operator -Platform Manager	-Design robustness - Cost cutting	Failure to isolate leaking valve which allowed a mixture of fluids and vapour into the starboard EDT. Also closeness of the EDT to the seawater firefighting service pipes and placement in the columns significantly contributed to the disaster. This design error was influenced by cost reduction. After the explosion, the EDT firefighting system was damaged and the rig began to sink Efforts to stabilize the unit failed as operators pumped

🟥						water into the opposite column. Unfortunately, the flood speed into one side of the column was too much to handle Reserve buoyancy in the form of air injection was available and functioned for evacuation purposes
D. Prevent fatalities	1. Operation and maintenance	- Ventilation damping actuators	- Maintenance standards	- Shift manager -Supervisor	- Quality Procedure - Safety culture -Inspection - Quality procedures - supervision	**PARTIAL FAILURE** Ventilation damper's actuators failed to function due to poor maintenance. The fire brigade actions and ventilation ducts that open watertight doors allowed the flow of gas to an ignition source thereby causing an explosion. The explosion led to the death of 11 personnel Reserve buoyancy functioned for evacuation of 138 personnel. 138 personnel that were not involved in the emergency operations were safely evacuated by crane and personnel transfer basket.
	2. Evacuation system	- Evacuation routes - Safety devices - Muster area	- Alarm response by personnel - Rescue operations - Evacuation vessel contact	- Emergency response team - Rescue teams - Platform manager	- Leadership - safety equipment accessibility - Competence - Evacuation training - Response timing - Reporting - Decision making ability - Communication	
	3. Communication system	- Alarm - Public address system - other communication channels	- Operator - Platform manager	- Internal communication - External communication	-Communication channels - Instruction clarity -Response timing	

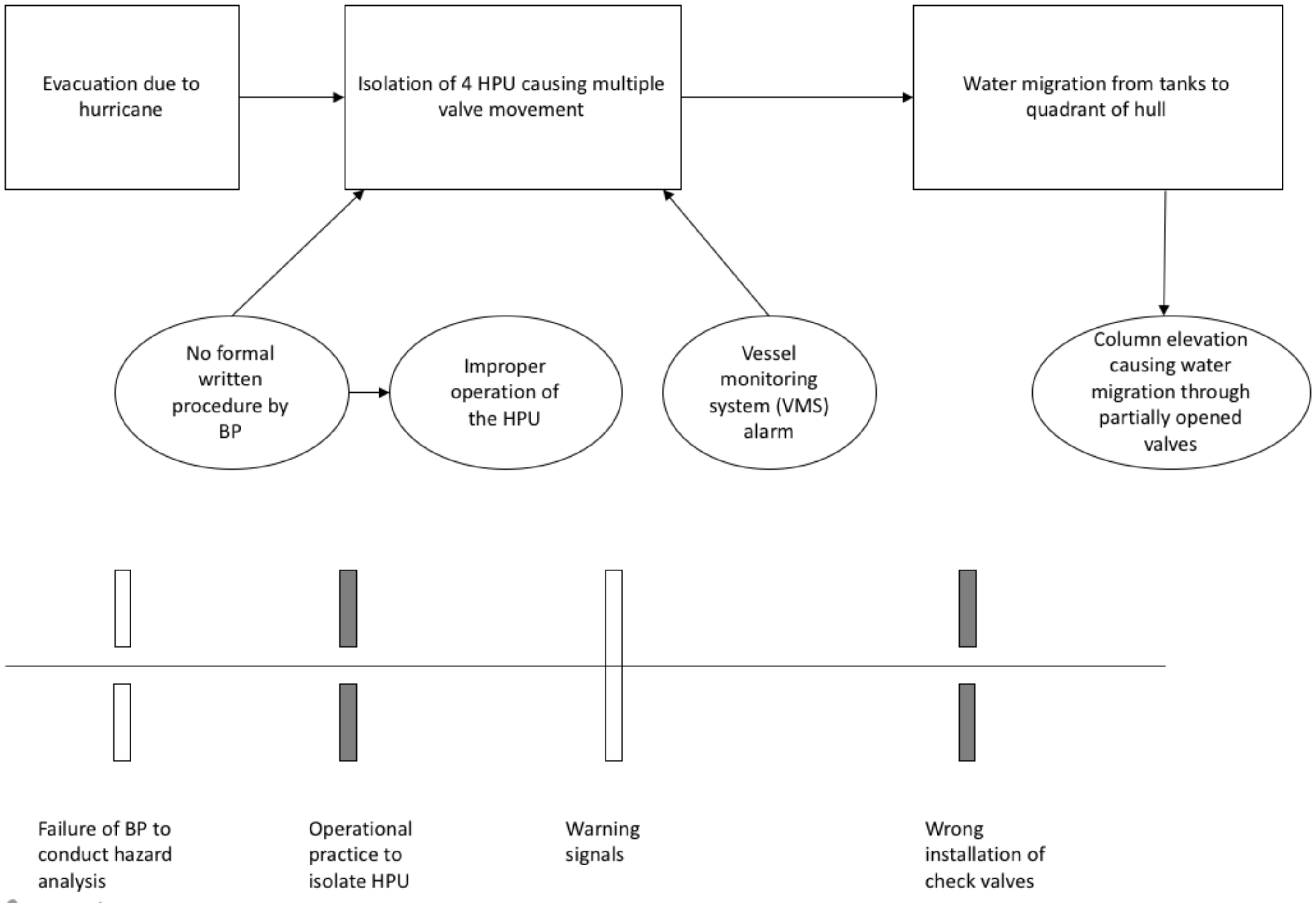


Figure D- 7: THUNDER HORSE (2005)

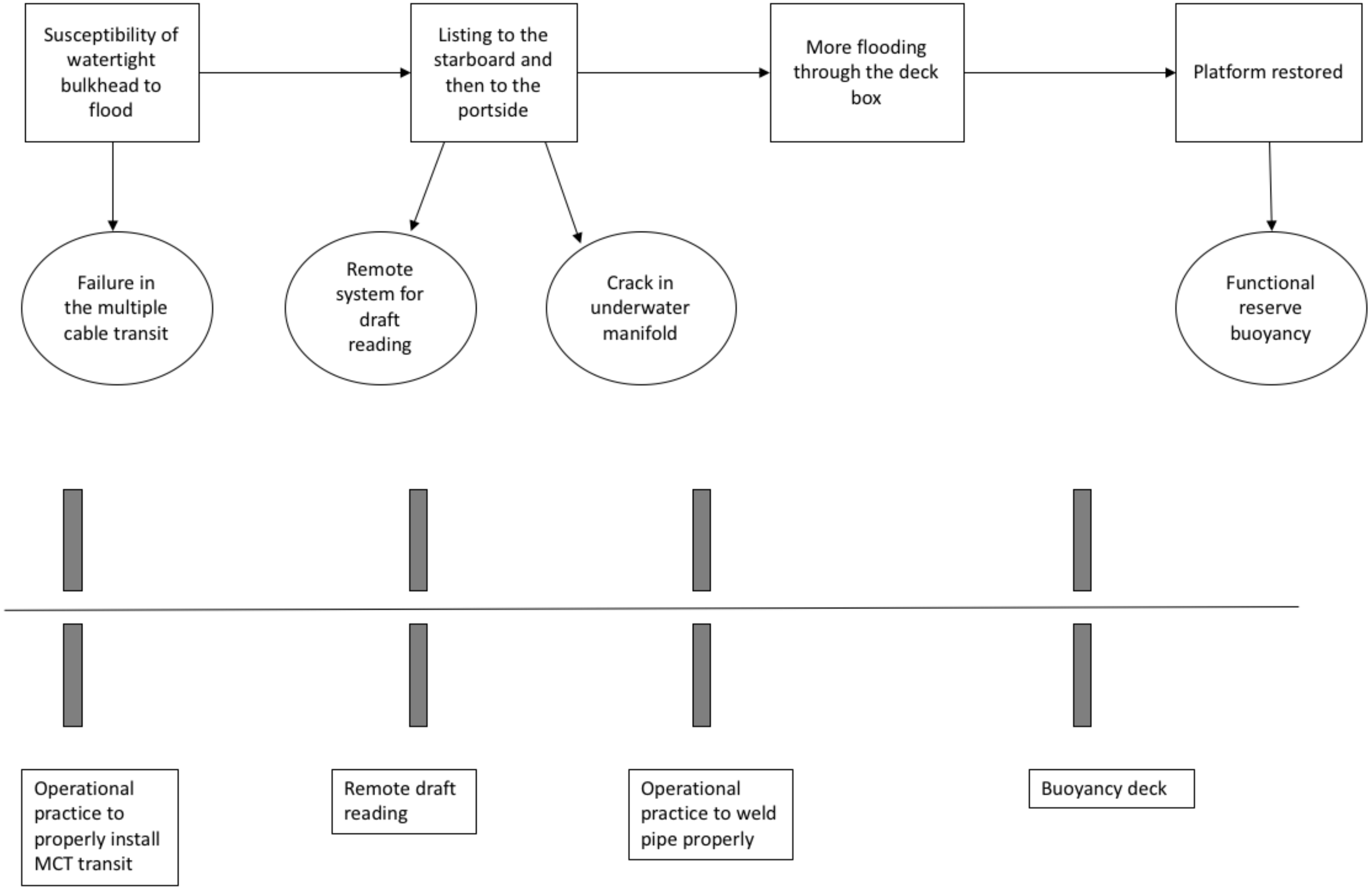


Figure D- 8: THUNDER HORSE (2005) (Contd.)

Performance colour codes

Red = Barrier failure
Yellow = Partial barrier failure
Green = Barrier success

Glossary

HMI = Human Machine Interference
HPU = Hydraulic Power Unit
MCT = Multiple Cable Transit
N/A = Not Applicable

*Table D- 6;*Thunder Horse accident barrier performance table. *Source*; Bsee, (n.d)

Barrier functions	**Barrier System**	**Barrier Element**			**Risk Influencing Factors**	**Barrier Performance**
		Technical	Operational	Organisational		
A. Maintain Structural Integrity and Marine Control	1. Hydraulic Control System and Isolation	- Control room -Remote system -Control panel - HPU controls -HPU back-up system -Alarms	- Monitor system - Alarm response	- Operator	-Response time - Decision making training -Competence - Human-machine interface (HMI)	**FAILURE OF BARRIER** Failure of BP to establish operating procedures for the Hydraulic Power Unit (HPU) that controls the bilge and ballast systems. This caused the rig to be vulnerable to extreme weather. The crew lacked expertise to successfully isolate the HPU. This caused the valves to make several movements, thereby allowing water ingress in the unit. Failure of BP to conduct a
	2 Operations and Maintenance	-Maintenance standards and guides	-Permit to Work System -Maintenance manual	-Operator - Platform manager -Supervisor	- Safety culture -Inspection - Quality procedures - supervision	
	3 Design Safety	- Industrial standards	-Quality audits	- Design team	-Safety critical expertise - Safety culture -Design procedure	

					-Technical condition -Industrial standard conformance	hazard and operability (HAZOP) study of the HPU so as to identify potential hazards that could occur during operation of the HPU system. The remote system was unavailable when needed for draft reading thereby, resulting to open deadlights Insufficient robust design of the components in the control panel. They were not designed to be protected against sea water Lack of training programs and operational manuals. This reflected in the decision making of two operators, as they did not close the deadlights during the storm.
B. Prevent Escalation of Initiating Failure	1. Ballast control console	Emergency detectors -Alarms -Detect leakage - ballast valve actuators -Sensor tube	-Respond to detectors - Swift response to alarms	-Operator -Platform Manager	- Communication - Condition of tech. systems - Operating procedures - Experience - Work practice -Weather -Response time -Action criteria -Design robustness	**FAILURE OF BARRIER** Lack of expertise by the MCT Brattberg personnel. They failed to properly install the right configuration for the MCTs. This led to spaces in the bulkhead to be filled with blank blocks
	2. Pumping and draining system	-Communication systems -Pumps	- Pumping and draining drills	-Operator		Failure of operator to inspect the installation of the MCTs

	3. Operations and maintenance	-Emergency drain tanks - Maintenance standards and guides	-Maintenance manual -Inspection	-Operator - Platform manager -Supervisor	- Safety culture -Inspection - Quality procedures - supervision	Faulty installation of check valves in the bilge system by the operator. This led to the migration of ballast water into manned spaces in the hull The forward tanks did not <u>function</u> as expected (i.e., emptying function) due to low capacity of the pumps
C. Prevent Total Loss	1. Flood control system (Reserve buoyancy)	-Chain lockers - Underwater manifold - Ballast valve actuators -Sensor tube -Control panel -Ballast valves -Sea chest valves -Discharge valves -Check valves -Ballast pumps -Buoyancy reserve	- Inspection	- Operator -Platform Manager	- Safety culture -Design procedure -Technical condition Response time -Action criteria -Response time -Familiarization	**FAILURE OF BARRIER** Failure to inspect all possible downflooding places and water/weather tight barriers. After the incident, the repair personnel found out that there was crack in the underwater manifold. This was due to failure to weld pipes properly. The rig's reserve buoyance <u>functioned</u> (buoyant deck). This made it possible to avoid of total loss of the rig, hence righted six weeks later
	2. Equipment protection system	-Sensors -Control valve	-Monitor system -Operate valves	-Operators	-Design robustness -Design procedure	
	3. Water/weather tight integrity	-Water tight doors -Bulkheads Industrial standards - Hatchways - Machinery space openings - Ventilators	-Condition monitoring	- Operator -Platform Manager		

		- Air pipes - Inlets and discharges - Freeing ports				
D. Prevent fatalities	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**

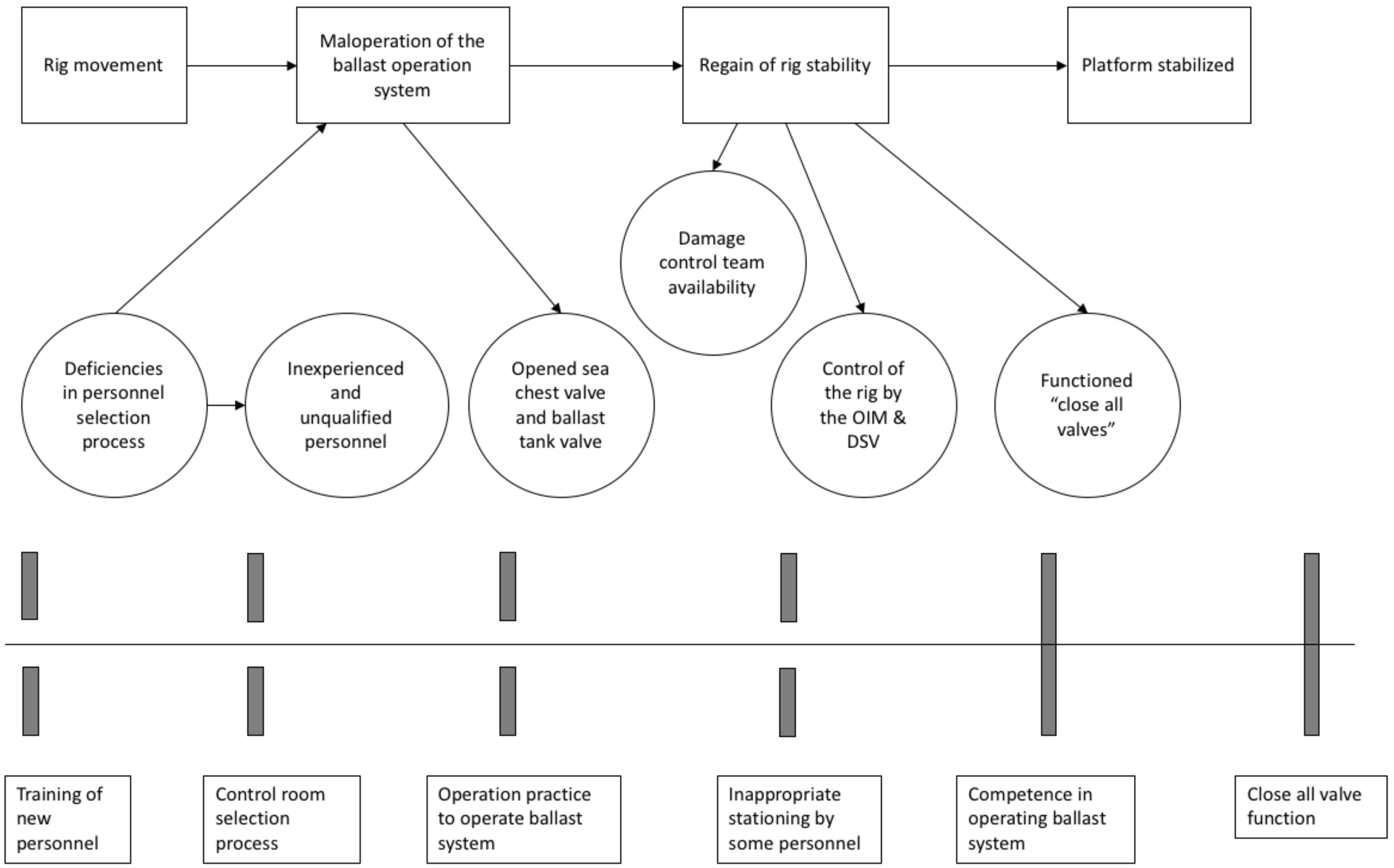


Figure D- 9: SCARABEO 8 (2012)

Glossary

HMI = Human Machine Interference
DSV = ENI Drilling Supervisor
N/A = Not Applicable
COOP = Control room operator

Performance colour codes

Red = Barrier failure
Yellow = Partial barrier failure
Green = Barrier success

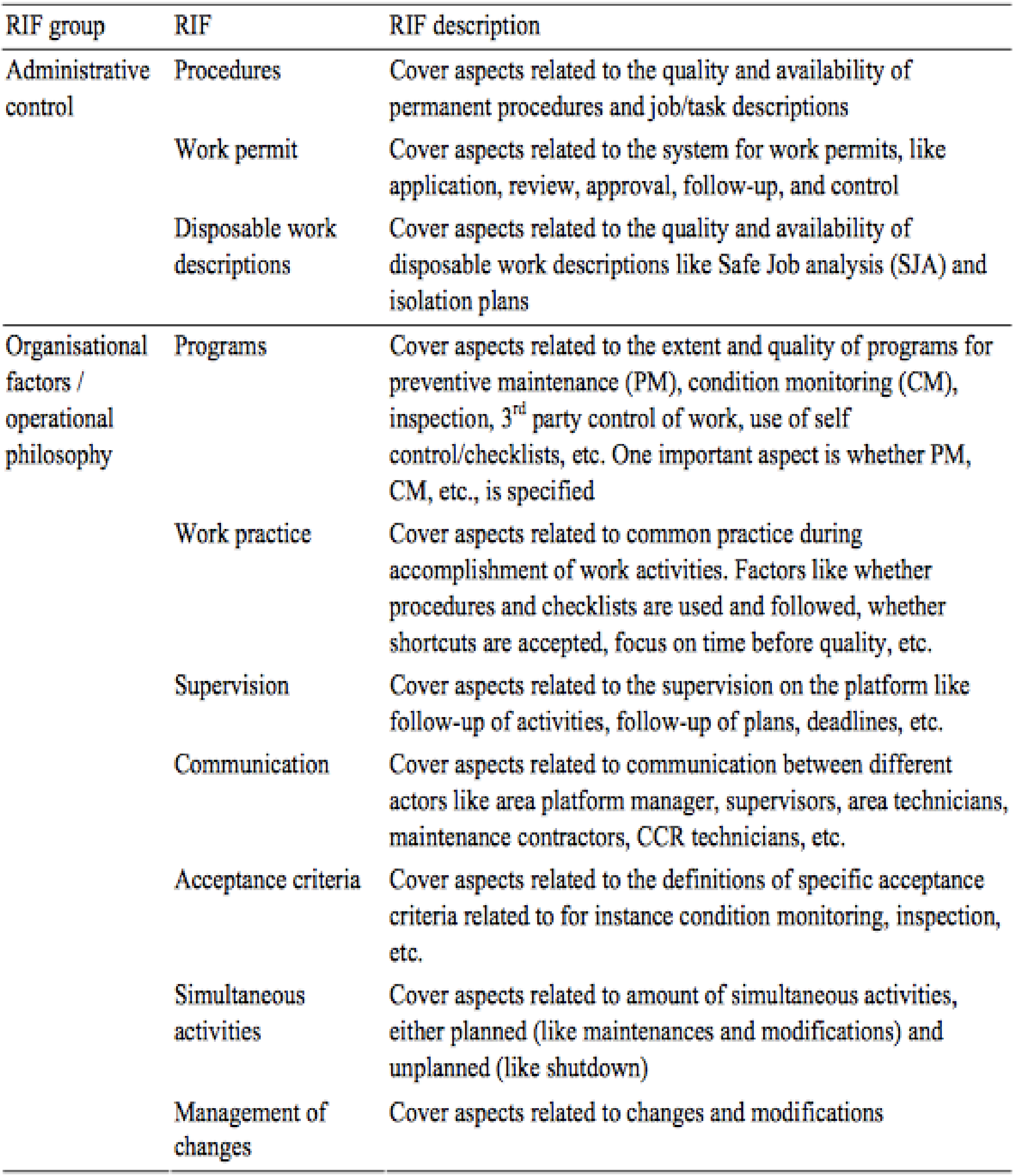
Table D- 7;: Scarabeo 8 accident barrier performance table Source; Sandberg et al., (2012)

Barrier functions	**Barrier System**	**Barrier Element**			**Risk Influencing Factors**	**Barrier Performance**
		Technical	Operational	Organisational		
A. Maintain Structural Integrity and Marine Control	1 Ballast Control System	-Ballast control room -Remote system -Control panel - Ballast valves -Alarms -Bridge handover	- Monitor system -Operate valves	- Operator -Shift workers - Shift manager -Supervisor	-Response time - Decision making training -Competence - HMI	**FAILURE OF BARRIER** Lack of competence on the bridge incident, because the on duty COOP was not sufficiently trained for ballast control tasks**.** Valves were opened to compensate for the 7 degrees list by the on duty control room operator. This led to the flow of water into the 1189 m^3 tank The HMI on the Ballast Control System and the bridge was not optimal. This made the identification of the opened aft sea chest valve difficult.

B. Prevent escalation of initiating failure	1 Ballast control console	-Emergency detectors -Alarms -Public address system - ballast valve actuators -Sensor tube	-Respond to detectors - Swift response to alarms	-Operator -Platform Manager	- Communication - Condition of tech. systems - Operating procedures -Experience - Work practice -Response time -Action criteria -Design robustness	**SUCCESS OF BARRIER** The general alarm and public address system functioned properly and crew members were ordered to muster at the temporary refuge Expertise and mobilization time was attained as there was decisive intervention by the OIM and experienced Eni DSV in controlling the situation
	2 Emergency Shutdown system	-Emergency detectors -Alarms -Emergency cut off electricity and air supplies to ballast system	-Respond to detectors - Swift response to alarms	-Emergency support vessel crew -Platform Manager	-Emergency response training	The “close all valves” function in the Ballast control system functioned when activated.
C. Prevent total loss	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**	**N/A**
D. Prevent fatalities	1. Evacuation system	- Evacuation routes - Safety devices - Muster area	- Alarm response by personnel - Rescue operations - Evacuation vessel contact	- Emergency response team - Rescue teams - Platform manager	- Leadership - safety equipment accessibility - Competence - Evacuation training - Response timing - Reporting - Decision making ability	**PARTIAL FAILURE** As at the time of the initial alarm, control of personnel was not attained at the acceptable time frame. This made the damage control procedure to be partially ineffective. Some workers in the damage control team went to the life boats instead of reporting to the muster area. They

	2. Communication system	- Alarm - Public address system - other communication channels	- Internal communication - External communication	- Operator - Platform manager	-Communication channels - Instruction clarity -Response timing	claimed they heard the “abandon rig” alarm

Table D- 8; Description of Risk Influencing Factors. *Source* Sklet et el., 2006



RIF group	RIF	RIF description
Administrative control	Procedures	Cover aspects related to the quality and availability of permanent procedures and job/task descriptions
	Work permit	Cover aspects related to the system for work permits, like application, review, approval, follow-up, and control
	Disposable work descriptions	Cover aspects related to the quality and availability of disposable work descriptions like Safe Job analysis (SJA) and isolation plans
Organisational factors / operational philosophy	Programs	Cover aspects related to the extent and quality of programs for preventive maintenance (PM), condition monitoring (CM), inspection, 3rd party control of work, use of self control/checklists, etc. One important aspect is whether PM, CM, etc., is specified
	Work practice	Cover aspects related to common practice during accomplishment of work activities. Factors like whether procedures and checklists are used and followed, whether shortcuts are accepted, focus on time before quality, etc.
	Supervision	Cover aspects related to the supervision on the platform like follow-up of activities, follow-up of plans, deadlines, etc.
	Communication	Cover aspects related to communication between different actors like area platform manager, supervisors, area technicians, maintenance contractors, CCR technicians, etc.
	Acceptance criteria	Cover aspects related to the definitions of specific acceptance criteria related to for instance condition monitoring, inspection, etc.
	Simultaneous activities	Cover aspects related to amount of simultaneous activities, either planned (like maintenances and modifications) and unplanned (like shutdown)
	Management of changes	Cover aspects related to changes and modifications

RIF group	RIF	RIF description
Personal characteristics	Competence	Cover aspects related to the competence, experience, system knowledge and training of personnel
	Working load / stress	Cover aspects related to the general working load on persons (the sum of all tasks and activities)
	Fatigue	Cover aspects related to fatigue of the person, e.g., due to night shift and extensive use of overtime
	Work environment	Cover aspects related to the physical working environment like noise, light, vibration, use of chemical substances, etc.
Task characteristics	Methodology	Cover aspects related to the methodology used to carry out a specific task.
	Task supervision	Cover aspects related to supervision of specific tasks by a supervisor (e.g., by operations manager or mechanical supervisor)
	Task complexity	Cover aspects related to the complexity of a specific task.
	Time pressure	Cover aspects related to the time pressure in the planning, execution and finishing of a specific task
	Tools	Cover aspects related to the availability and operability of necessary tools in order to perform a task.
	Spares	Cover aspects related to the availability of the spares needed to perform the task.
Characteristics of the technical system	Equipment design	Cover aspects related to the design of equipment and systems such as flange type (ANSI or compact), valve type, etc.
	Material properties	Cover aspects related to properties of the selected material with respect to corrosion, erosion. fatigue, gasket material properties, etc.
	Process complexity	Cover aspects related to the general complexity of the process plant as a whole
	HMI (Human Machine Interface)	Cover aspects related to the human-machine interface such as ergonomic factors, labelling of equipment, position feedback from valves, alarms, etc.
	Maintainability/ accessibility	Cover aspects related to the maintainability of equipment and systems like accessibility to valves and flanges, space to use necessary tools, etc.
	System feedback	Cover aspects related to how errors and failures are instantaneously detected, due to alarm, failure to start, etc.
	Technical condition	Cover aspects related to the condition of the technical system