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# Enabling Formal Safety Assessment Method in Jack-Up Rig Operations

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**ABSTRACT:** *Since the inception of jack-up rig operations in the early 1950s, series of hazardous accidents has been witnessed, and losses recorded. These events are approximated to occur at least twice in a year. With this statistics, the harsh offshore environment demands jack-ups of premium quality. Designing a premium self-elevating (jack-up) offshore structure is one that must be founded on well-proven principles, industry-accepted reliability techniques and criteria. Construction must also follow a suitable classification society's guidelines for the different aspects and phases of the jack-up.Before designing and constructing a jack-up which can optimally operate within the harsh offshore environment, identifying the hazards associated with the structure in this environment and how to mitigate or manage them is essential. The Formal Safety Assessment (FSA) is the methodology employed in the maritime industry to identify and check these marine hazards, and to design ways to bring them under control in a cost effective manner. The five steps in FSA are hazard identification, risk assessment, risk control option, cost benefit analysis/assessment, and decision making steps. In this paper, the jack-up rig was introduced and its operation principle explained from the transit mode to the operation mode offshore. The hazards associated with self-elevating units were identified using the Preliminary Hazard Analysis (PHA). The Capsizing Hazard which was identified as critical was considered and analyzed using the Fault Tree Analysis (FTA). Consequently, the Fishbone Diagram was used to analyze, state the root cause of capsizing of jack-up structures through the risk factors of sampled incident cases, and recommend measures to curb the special problem. Some recommended measures are a bolster of existing guidance. Recommendations and improvements on how to eliminate or reduce capsizing of jack-ups through early design and construction, and before in-service operation were made.*

**KEYWORDS:** jack-up, risk, offshore, fault tree analysis, root cause and capsizing.

## INTRODUCTION

A **Jack-Up Rig** is a type of mobile platform composed of a hull, legs and a jacking system. The jacking system raises the legs and allows it to be towed to a site. On site, it lowers the legs into the seabed, thereby elevating the hull to provide a stable work deck for operations. The hull is raised by motors through pinions which rotates along racks on the legs (Figure 1) or through the 'pin and hole' special mechanism (Figure 2). Originally, jack-ups were meant for use in shallow waters. However, their economic importance with respect to their combined mobility and fixed structure behavior in operational condition has raised calls for their use in deeper waters. Before drilling commences at any site, the jack-up legs are preloaded to pre-determine the maximum loads on the legs which is supported by the seabed. This preloading ensures that after the jack-up is jacked to full air-gap (height between the elevated hull from the keel and the sea level) and experiences environmental and operating loads, that the supporting soil will provide a reliable foundation.

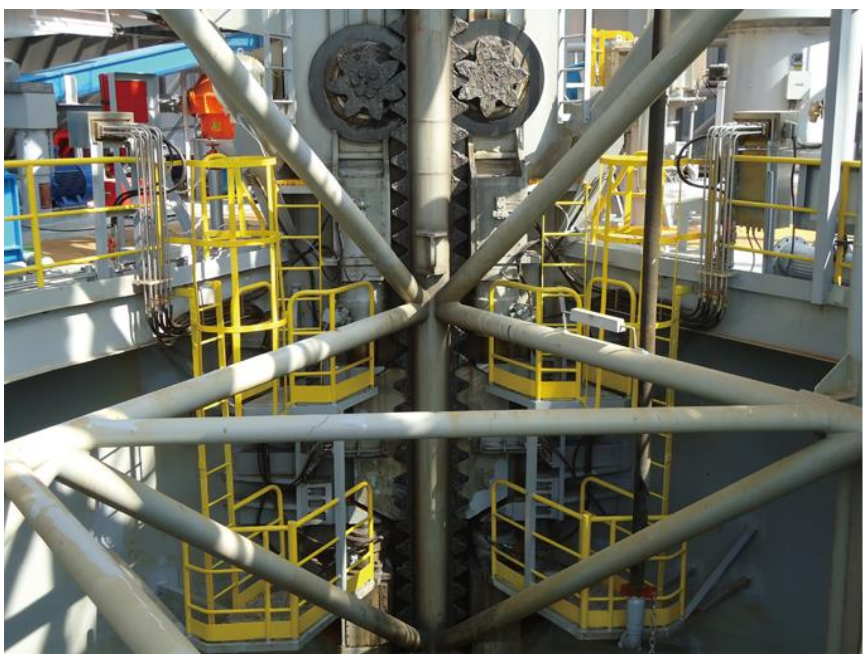

**Figure 1.** Rack and Pinion jacking system (sagta.com, 2018)

**Figure 2.** Pin and Hole mechanism (Hercules offshore, 2022)

Offshore structures are generally designed with indispensable requirements to be reliable, and to have a long and safe operating or functional life with the risk of catastrophic failures mitigated to the lowest minimum. Studies has shown that jack-ups have failed more than any other type of offshore structure used in the offshore environment (Figure 3), and a significant percentage of these failures were a result of inadequate design which failed to properly consider factors that can cause operational breakdown in service, improper evaluation of structural elements, and erroneous use of calculation methods.

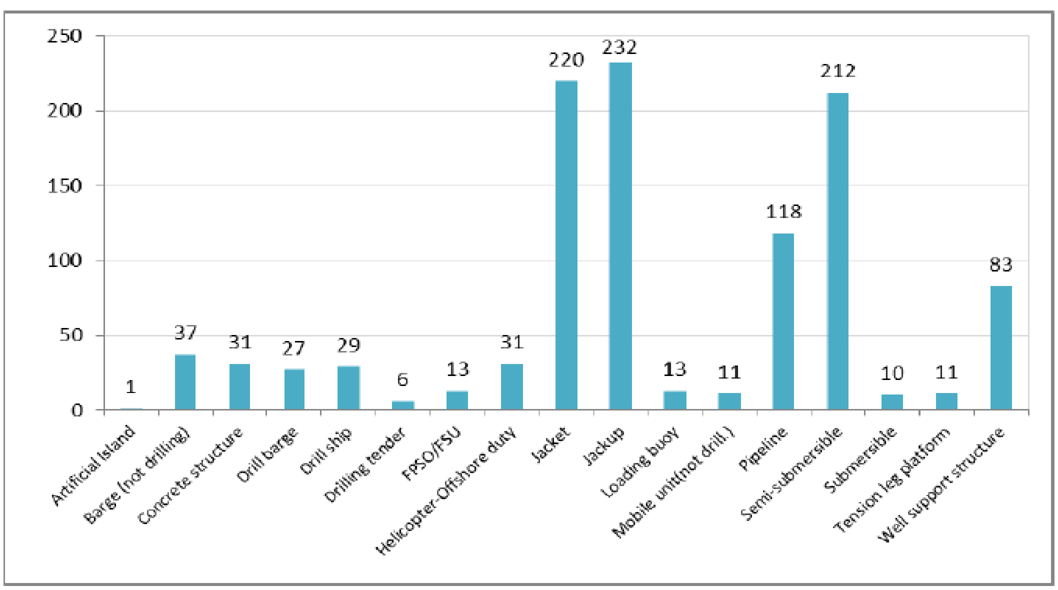


**Figure 3.** Distribution of accidents by offshore structure type (Vamanu B. et al., 2016)

Further studies and reports on the accident analysis has proven that a significant number of these offshore losses, especially that of jack-ups occurred through Capsizing and Fatigue (Figure 4). Some of the catastrophic jack-up accidents recorded includes the Sea Gem jack-up rig accident in British waters with 19 fatalities in December 1965 (Dejan and Pavel, 2021). Material failure caused by corrosion led to capsizing of this jack-up; Gemini jack-up rig incident in the Gulf of Suez with 18 fatalities in October 1974 (Dejan and Pavel, 2021). The structural legs buckling under load led to capsizing of the unit; Ocean Express jack-up rig incident in Mexican waters with 13 fatalities in 1976 (Dejan and Pavel, 2021). This accident was caused by limited knowledge of vessel stability, installation error which led the inadequately supported pipe on the deck to cause a deck list when it moved, and severe weather conditions; Bohai 2 jack-up rig accident in Chinese waters with 72 fatalities in November 1979 (Dejan and Pavel, 2021). Installation error from the incorrect stowing of deck equipment which led to the damage of the deck under tow and subsequent flooding was the main cause of this accident; Qatar 1 jack-up rig incident in the Arabian Gulf with 20 fatalities in December 1956 (Dejan and Pavel, 2021); Bohai 3 jack-up rig accident in Chinese waters with 70 fatalities in June 1980 (Dejan and Pavel, 2021); Hasbah 6 jack-up rig accident in the Persian Gulf with 19 fatalities in October 1980 (Dejan and Pavel, 2021), etc. Similarly, the catastrophic fire and explosion accident of Piper Alpha platform in British waters with 167 fatalities in July 1988 (Dejan and Pavel, 2021) led the British government to introduce regulations that required any operator of every mobile and fixed installation that operates in British waters to submit a Safety Case. Also, this accident led to the implementation of Safety Case Regulations in 1993 and the implementation of Design and Construction Regulations in 1996 by the International Maritime Organization (IMO) (Olav and Bjorn, 2011). The fire and explosion was as a result of leakage of gases from a condensate pump at the time of general reconstruction.

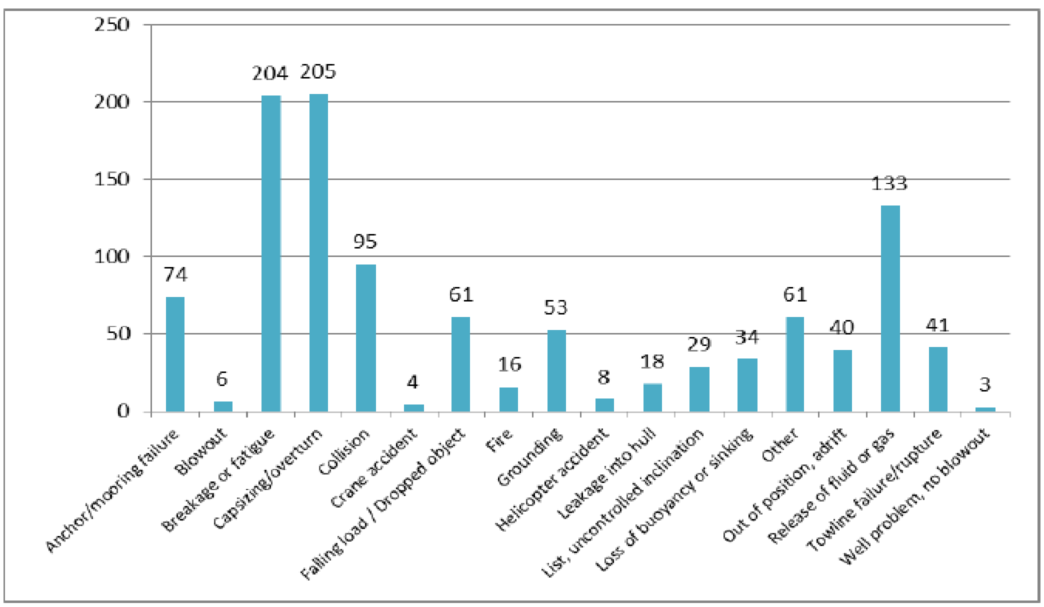


**Figure 4.** Distribution of accidents by final outcomes (Vamanu B. et al., 2016)

From the numerous reports of jack-up accidents, it is often not so easy to make a clear distinction among the root causes of the accidents. For example, it is always not clear if procedural failures or human factors were of greatest cause (predominant). To unriddle the uncertainty regarding the main cause of these jack-up accidents, there is need to analyze the accidents through the most frequent recorded final outcome (Capsizing). To achieve this, a proper risk assessment method must be employed in evaluating the most important events associated with capsizing while a proper root cause technique must be employed to unmask the predominant cause of capsizing.

Presented in this paper is the Formal Safety Assessment, and the Fault Tree Analysis (FTA) risk assessment technique which was used to estimate the system reliability (against capsizing) and lifetime of the jack-up in the presence of fatigue, corrosion, installation error, defects in material and seabed collapse. First, the individual probability of failure of each risk factor was calculated using an exponential distribution function. The probability of failure of the jack-up system was then computed using the FTA expert judgment expansion formula. Important agents that increases the chances of a risk occurring were identified through a careful observation of the sequences of the threats in the risk control option and controlling options were given. Conclusions and decisions were drawn from the cost benefit analysis through the comparison of the costs of risk mitigation and damage, and the best risk management tactic to ensure the optimal performance of the jack-up system was recommended. Finally, the '*Fishbone'* root cause analysis technique was used to determine the predominant cause of capsizing hazard.

An advantage of this technique is that it can accurately make clear the predominant cause of a special problem through its deep analysis and is also able to recommend measures that will substantially correct or reduce the symptoms that contribute to the emergence of the problem.

## METHODOLOGY

### Formal Safety Assessment (FSA)

In the maritime industry, conducting a formal safety assessment is a way to ensure that an action is taken in advance before a disaster occurs. The International Maritime Organization, IMO described the FSA as a balanced, non-contradictory and systematic process directed at assessing the risks associated with shipping activity and evaluation of the costs and benefits of minimizing these risks. The FSA was originally developed in response to the July 1988 Alpha Piper offshore platform explosion in the North Sea which claimed the lives of about 167 persons. This particular accident informed maritime authorities of the need to develop a formal methodology which will be used for safety risk analysis in order to tackle disasters before they happen. This is how the IMO guidelines for Formal Safety Assessment came about. Over the years, the guidelines have undergone amendments which pointed out the need to objectively review data on incident reports, close-calls and operational failures, and for their reliability, uncertainty or ambiguity and validity to be assessed as well as reported. These amended versions also stressed the need for made assumptions and limitations of these data to be reported too.

According to the IMO, Formal Safety Assessment is a structured and systematic methodology of enhancing maritime safety which includes protection of life at sea, the marine environment and marine structure, by using risk assessment and cost benefit analysis. An FSA is completed in five steps which covers all aspects of proper safety analysis and suggests suitable safety measures against all threats. The five steps of FSA are:

1. Identification of Hazards (lists all relevant hazards, their potential causes, effects and severity);
2. Risk Assessment (evaluates the risk factors);
3. Risk Control Options (devises regulatory measures to mitigate and reduce all identified risks);
4. Cost Benefit Analysis (analyzes and measures the cost effectiveness of individual risk control option); and
5. Decision Making (recommends actions that should be taken).

In a straightforward manner, the steps can be reduced to:

1. What problems are obtainable? = identification of hazards
2. What is the likelihood of occurrence of the special problem(s) of interest? = risk assessment
3. How will the situation be improved? = risk control options
4. What would the situation improvement cost and the expected benefit after improvement? = cost benefit analysis
5. What action is best to ensure benefit maximization? = decision making.

FSA is very important because it encourages satisfactory compliance with the regulatory frameworks of the maritime industry and leads to improved safety and protection of the environment. FSA is quite technical and complex, and offers a headway and means of escaping from dilemma (IMO, 2019). Hence, the integrity of any marine structure is dependent on its FSA and the effectiveness of it.

For the sake of this study, the Preliminary Hazard Analysis method is the preferred qualitative method we will be employing in the identification and classification of the hazards peculiar to jack-ups in the offshore environment.

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## APPLICATION OF FSA TO JACK-UP RIG STRUCTURES

### Hazard Identification

**Preliminary Hazard Analysis (PHA)**

| 1.Hazards identified | 2.Causes of hazardous events | 3.Effects of hazardous events | 4.Classification of events (Severity) | 5.Preventive measures |
|---|---|---|---|---|
| 1.Collision/Impact | a) Structural fatigue of legs<br>b) Human error | a) Loss of life and property | Moderate | a) Alertness<br>b) Use of good materials |
| 2.Fire/Explosion | a) Human error<br>b) Faulty electrical component | a) Damage of jack-up rig<br>b) Loss of life | Catastrophic | a) Provision of temperature sensors<br>b) Provision of fire alarm system<br>c) Provision of fire extinguishers<br>d) Provision of water sprinkler systems |
| 3.Loss of position | a) Human error<br>b) Faulty navigation equipment<br>c) Fatigue of legs/welded parts | a) Damage of jack-up rig | Negligible | a) Good and well-functioning equipment |
| 4.Helicopter accident | a) Human error<br>b) Improper/excess loading | a) Loss of life<br>b) Property damage | Catastrophic | a) Proper loading |
| 5.Towing accident | a) Human error<br>b) Fatigue failure of towing line<br>c) Power failure | a) Loss of towing line<br>b) Collision with nearby objects | Negligible | a) Use of good towing lines and cables |
| 6.Capsizing/Loss of stability | a) Fatigue failure<br>b) Human error | a) Loss of life<br>b) Damage of jack-up rig<br>c) Environmental pollution | Catastrophic | a) Use of adequate materials<br>b) Proper manufacturing<br>c) Steady assessment |
| 7.Structural failure | a) Fatigue due to stresses in structural components<br>b) Human error | a) Loss of life<br>b) Damage of property | Catastrophic | a) Use of quality materials<br>b) Stress relief and distribution treatment |
| 8.Crane accident | a) Human error<br>b) Overloading<br>c) Material defects | a) Damage of property<br>b) Possible loss of life | Moderate | a) Carefulness when working<br>b) Proper training of workers<br>c) Proper lubrication of the crane arms |
| 9.Kick and blowout | a) High pressure lines leakages | a) Explosion<br>b) Property damage | Moderate | a) Routine checks on high pressure lines for leakages<br>b) Use of blowout preventer |

The methods used in sourcing these hazards are Brainstorming and Literature Review.

**Table1.** The Preliminary Hazard Analysis of Jack-Up Hazards

### Risk Assessment

A risk assessment reviews the acceptability of risk in accordance with risk standards and criteria, and it suggests if a risk reduction measure is needed to be put in place. Risk assessment can be



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qualitative or quantitative. In line with the aim of the paper, we employed the Fault Tree Analysis (FTA) as our quantitative risk assessment tool.

**Fault Tree Analysis**

The Fault Tree Analysis is an inferential, prescriptive, and top to down technique that illustrates how risk factors that leads to a critical (top) event are combined logically using Boolean logic gates (usually AND and OR). The FTA allows this top event to be evaluated through the combination of the risk factors. As soon as the fault tree is constructed, the chance of failure of the system is computed using the expert judgment formula – the *Cut Set Analysis* technique. The *cut sets* assigns unique labels (capital letter alphabets) to each risk factor. "A or B or C, A or BC, A or B or C or D" are examples of cut sets. In this study, the choice of the FTA quantitative method is because it better suites our analysis requirements which continued to grow in terms of complexity and level of detail (granularity). Finally, the quality of the result obtained with the FTA is highly dependent on the presumptuous fact that all the contributing factors which can facilitate the failure of the system have been amply identified (Schuller, 1997).

**Fault Tree Analysis Risk Assessment Technique**

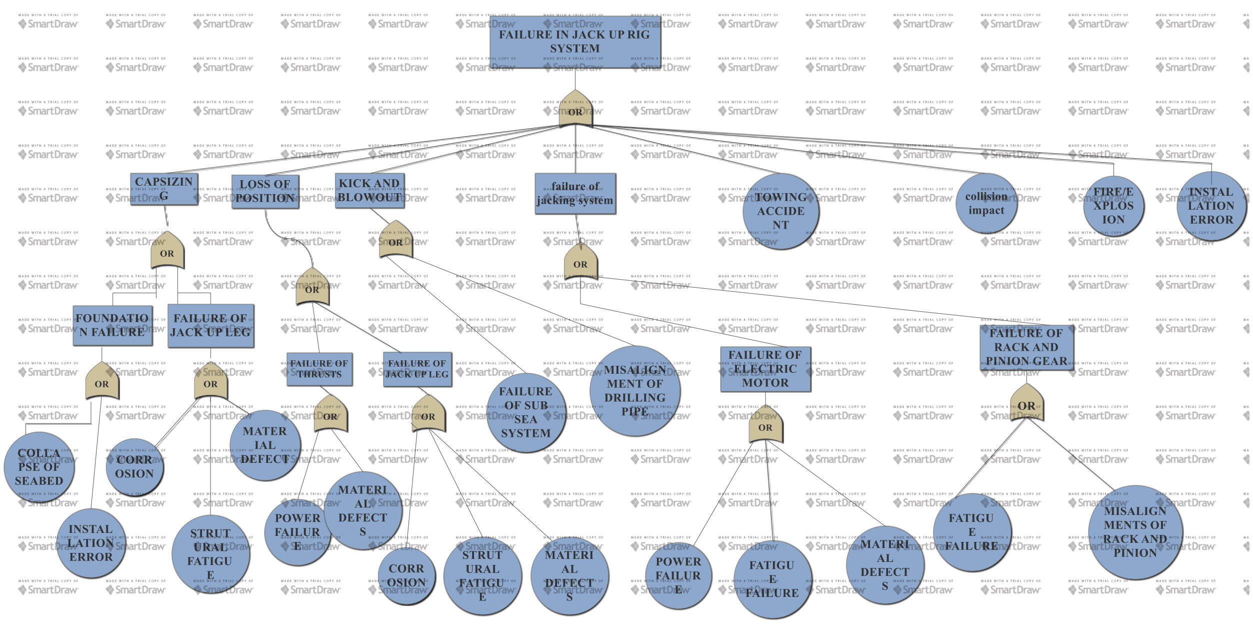


**Figure 5.** The Fault Tree Analysis Technique

For the top event (Failure of Jack-Up Rig System) to occur, either of the following must occur:

- *Capsizing*
- *Loss of position*

- *Kick and blowout*
- *Failure in jacking system*
- *Towing accident*
- *Collision/Impact*
- *Fire/explosion*
- *Installation error*

In-line with the objective of this paper, we will be focusing on **Capsizing** and the events that contributes to capsizing. For Capsizing to occur, either Foundation Failure (basic event) or Failure of Jack-Up Leg (basic event) must occur. For Foundation Failure to occur, either Collapse of Seabed (basic event) or Installation Error (basic event) must occur. For Failure of Jack-Up leg, either Corrosion, **Structural Fatigue** or Material Defect must occur. Thus:

A. Collapse of seabed
B. Installation error
C. Corrosion
D. Structural fatigue
E. Material defects

**Probabilities of Failure at Basic Event Level**

For this study, the choice of probability of failure will be depending on two factors. Factor 1 will be considered only:

1. The jack-up is in continuous operation and non-repairable.
2. The jack-up is in continuous operation and repairable.

Considering factor 1, the probability of failure in time (t) resulting from the occurrence of an event is P[X(t)]. Assuming exponential time to failure, P[X(t)] becomes:

$$\mathbf{P[X(t)] = 1-e^{-\lambda t}} \quad \textbf{(1)}$$

This assumption is validly justified here because exponential distributions are used as a rule (commonly) in calculations of product reliability and/or predicting how long a product will last. Therefore, for $\mathbf{P[X(t)] = 1-e^{-\lambda t}}$, $\mathbf{X}$ denotes a basic event, $\mathbf{t}$ denotes exposure time in hours, $\boldsymbol{\lambda}$ is failure rate, $\mathbf{P}$ is the probability of occurrence of each event. $\mathbf{e^{-\lambda t}}$ = System reliability parameter or survival function.

For non-repairable systems, the mean time to failure (MTTF) is one of basic measures of reliability. MTTF is the average time expected until the emergence of the first failure of a component of the system. For systems with constant failure rate, MTTF can be calculated by 1/λ, that is, failure rate inverse.

$$MTTF = \frac{1}{\lambda \text{ failures}/10^6 \text{hours}} \quad \textbf{(2)}$$

Therefore, considering minimum – maximum exposure or working times of between 10 years and 45 years. For the minimum time, conversion to hours: 10 years = 10×365×24=87600 hours. Assuming λ is not constant, take λ for each basic event to be $1.2\times10^{-6}$, $3.2\times10^{-6}$, $4.1\times10^{-6}$, $2.6\times10^{-6}$, and $5.4\times10^{-6}$ respectively.

The failure probabilities are:
$P(A) = 1-e^{-1.2\times10\text{^-}6\times87600} = 0.0998$
$P(B) = 1-e^{-3.2\times10\text{^-}6\times87600} = 0.2445$
$P(C) = 1-e^{-4.1\times10\text{^-}6\times87600} = 0.3017$
$P(D) = 1-e^{-2.6\times10\text{^-}6\times87600} = 0.2037$
$P(E) = 1-e^{-5.4\times10\text{^-}6\times87600} = 0.3769$

**Calculation of the Probability of Occurrence of the Top Event**

The OR gate with five input events (A, B, C, D and E).
➔ P (A+B+C+D+E) = P (A) +P (B+C+D+E) - P (AB+AC+AD+AE)

P(A)+P(B)+P(C+D+E)-P(BC+BD+BE)-{P(AB)+P(AC)+P(AD)+P(AE)-P(ABC+ABD+ABE)}

P(A)+P(B)+P(C)+P(D+E)-P(CD+CE)-{P(BC)-P(BD+BE)+P(BCD+BCE)}-P(AB)-P(AC)-P(AD+AE)+P(ACD+ACE)+{P(ABC)+P(ABD+ABE)-P(ABCD+ABCE)}

=>P(A)+P(B)+P(C)+P(D)+P(E)-P(DE)-P(CD)-P(DE)+P(CDE)-P(BC)-P(BD)-P(BE)+P(BDE)+P(BCD)+P(BCE)-P(BCDE)-P(AB)-P(AC)-P(AD)-P(AE)+P(ADE)+P(ACD)+P(ACE)-P(ACDE)+P(ABC)+P(ABE)-P(ABDE)-P(ABCD)-P(ABCE)+P(ABCDE)

Calculation using the expert judgment parameters:
0.0998+0.2445+0.3017+0.2037+0.3769-(0.2037×0.3769)-(0.3017×0.2037)-(0.2037×0.3769)+(0.3017×0.2037×0.3769)-(0.2445×0.3017)-(0.2445×0.3769)-(0.2445×0.2037×0.3769)+(0.2445×0.3017×0.2037)+(0.2445×0.2037×0.3769)+(0.2445×0.3017×0.2037×0.3769)+(0.0998×0.2445)-(0.0998×0.3017)-(0.0998×0.2037)-(0.0998×0.3769)-(0.0998×0.2037×0.3769)+(0.0998×0.3017×0.2037)+(0.0998×0.3017×0.3769)+(0.0998×0.3017×0.2037×0.3769)-(0.0998×0.2445×0.3017)+(0.0998×0.2445×0.2037)+(0.0998×0.2445×0.3769)+(0.0998×0.2445×0.3017×0.2037)-(0.0998×0.2445×0.3017×0.3769)+(0.0998×0.2445×0.2037×0.3769) = 0.8452.
➔0.8452×100 = **84.52%**.

**84.52%** probability of failure and **15.48%** probability of survival. This calculated probability of failure of the jack-up system is high and it clearly means that the system will catastrophically fail (capsize) in continuous use before 10 years. Therefore, it emphasizes the need to mitigate the associated risks of the *cut-set* factors for the elongation of the lifetime of the jack-up.

**Risk Control Option**

The risk control option study will help the analyst to understand the various ways through which the associated risks of the contributing factors can be eliminated or reduced. In other words, this step analyzes the threats and provides controlling options. In this paper, the Capsizing Hazard is considered as the most critical hazard and collapse of seabed, installation error, corrosion, structural fatigue and material defects were identified as the risk factors of Capsizing. The measurable options to control these risk factors will be looked at here.

- ***Collapse of seabed*** – the effects of an unexpected collapse of seabed which may be as a result of weak or varying soil foundation can be severe. Therefore, the risks associated with this risk factor can be minimized by carrying out a detailed site soils survey which should include borehole sampling and cone penetration (CPT) testing, legs preloading - one leg at a time, and air gap adjustment. At candidate site, when the air-gap is reduced, it helps to prevent any large vertical displacement through the buoyancy of the hull which can penetrate the waterline and produce a draught.
- ***Installation error*** – this error can lead to unnecessary vibrations and fatigue cracks which have risky effects such as the damage of lifting gears. Weight imbalance is also an installation error that could cause leg deformation and undermine overturning safety. These risks can be reduced or minimized by introducing vibration dampers where appropriate, ensuring that weight is evenly distributed using ballast tanks and that high-strength steels are used for the leg construction; even for the chords and racks.
- ***Corrosion*** – this is associated with the deterioration of the structural steel components of the jack-up by the varying temperature plus high salinity of seawater. Corrosion fatigue risk is associated with this deterioration. Corrosion can be detected by evaluating the properties of the structural materials and testing for internal flaws and defects using either of the following methods – visual inspection, non-destructive testing, ultrasonic testing and magnetic particle inspection. The corresponding corrosion fatigue risk can be mitigated to the lowest minimum by two principal methods – coatings and cathodic protection methods. Protective coatings are usually used for the barge while cathodic protection method is preferred for the legs.
- ***Structural fatigue*** – structural fatigue in structural elements are as a result of induced stresses in the elements when can come from welding or load variation. The risks associated with this stress fluctuations are cracks or fracture and distortion. Damage as a result of stress fluctuations is cumulative and unrecoverable. This is severe in welded joints. The steps to mitigating these risks are to first investigate the stresses in the plates or welded joints using either or both a finite element software and x-ray diffractometer, and conducting stress relief treatments using any of the stress relief treatment approaches – mechanical, heat and electromagnetic methods. In service, fatigue due to load variations can be modeled and simulated in ANSY, ABAQUS, etc., cracks or crack sizes estimated

and potential failure paths identified – fatigue analysis. Then, a stress relief solution is applied.

- ***Material defects*** – defects are risky because they have an unmatched influence on the internal properties and behaviour of the material, and can easily interact with other faults to cause a premature failure of the system in service. The risks associated with material defects such as fracture, fatigue, etc., are detrimental to the overall performance of the system in service. These risks can be controlled through the proper selection of materials at the design stage. Material defects can also occur during the fabrication stage of the offshore structure through welding. Welder defects can include hydrogen cracks, slag entrapment, lack of fusion, etc. The risks associated with material defect from welding which can change the microstructure of the joined materials can be minimized by managing the rate of heat input at joints. Heat input per length is given by: $\frac{V\,x\,A\,x\,60\,x\,k}{1000\,x\,S}$ kJ/mm.
  $S$ = welding speed (mm/min)
  $A$ = welding current (Amperes)
  $V$ = arc voltage (Volts)
  $k$ = thermal efficiency factor.

**Cost Benefit Analysis**

The cost benefit analysis aids in understanding the cost involved in the chosen risk control option. This quantification analysis often quantifies the risk control cost and that of damage cost, and for the analysis to be accepted, the cost of risk control/prevention **MUST** be less than the damage cost. Hence, before starting a new project, it is prudent to conduct a cost benefit analysis which evaluates the financial costs of the project and analyze the financial benefits the project is expected to yield after completion. The cost-benefit feasibility outcome of this analysis is instrumental in the decision making processes. In offshore risk assessment, this analysis quantifies the cost of preventing or controlling a risk and the cost of damage that can result from the uncontrolled risk.

1. **Threat:** Collapse of seabed
   **Probability of failure ($P_f$):** 0.0998

| Risk | Control option | Risk value = $P_f$ * Dc (USD) | Cost of mitigation (USD) | Damage cost (Dc) (USD) |
|---|---|---|---|---|
| **Weak soil foundation risk** | Site survey | $2,228,791 | $588,577 | $22,332,581 |
| **Air gap risk** | Reducing air-gap | $83,549 | $0 | $837,168 |
| | | **Total** | **$588,577** | **$23,169,749** |

2. **Threat:** Installation error
   **Probability of failure ($P_f$):** 0.2445

| Risk | Control option | Risk value = $P_f$ * Dc (USD) | Cost of mitigation (USD) | Damage cost (Dc) (USD) |
|---|---|---|---|---|
| **Vibration risk** | Dampers | $163,197 | $416 | $667,475 |
| **Fatigue crack risk** | High-strength steel | $3,285 | $789 | $13,437 |
| **Weight distribution risk** | Ballast tanks | $17,468 | $12,741 | $71,446 |
| | | **Total** | **$13,946** | **$752,358** |

3. **Threat:** Corrosion
   **Probability of failure ($P_f$):** 0.3017

| Risk | Control option | Risk value = $P_f$ * Dc (USD) | Cost of mitigation (USD) | Damage cost (Dc) (USD) |
|---|---|---|---|---|
| **Corrosion fatigue risk** | Coating protection and/or Cathodic protection | $19,298 | $2,851 | $63,963 |
| | | **Total** | **$2,851** | **$63,963** |

4. **Threat:** Structural fatigue
**Probability of failure ($P_f$):** 0.2037

| Risk | Control option | Risk value = $P_f$ * Dc (USD) | Cost of mitigation (USD) | Damage cost (Dc) (USD) |
|---|---|---|---|---|
| **Fracture and distortion risks** | Stress relief solution | $1,292,171 | $84,332 | $6,343,500 |
| | | **Total** | **$84,332** | **$6,343,500** |

5. **Threat:** Material defects
**Probability of failure ($P_f$):** 0.3769

| Risk | Control option | Risk value = $P_f$ * Dc (USD) | Cost of mitigation (USD) | Damage cost (Dc) (USD) |
|---|---|---|---|---|
| **Unsuitable material risk** | Proper selection | $15,409,451 | $14,654,321 | $40,884,719 |
| **Microstructure change risk** | Heat input control | $3,497,050 | $82,000 | $9,278,456 |
| | | **Total** | **$14,736,321** | **$50,163,175** |

**Table 2.** Case study results for the Capsizing Hazard

| Threat | Probability | Risk value = $P_f$ * Cc (USD) | Cost of mitigation (USD) | Consequence cost (Cc) (USD) |
|---|---|---|---|---|
| **Collapse of seabed** | **0.0998** | **$2,312,340** | **$588,577** | **$23,169,749** |
| **Installation error** | **0.2445** | **$183,950** | **$13,946** | **$752,358** |
| **Corrosion** | **0.3017** | **$19,298** | **$2,851** | **$63,963** |
| **Structural fatigue** | **0.2037** | **$1,292,171** | **$84,332** | **$6,343,500** |
| **Material defects** | **0.3769** | **$18,906,501** | **$14,736,321** | **$50,163,175** |
| | **Total** | **= $22,714,260** | **= $15,426,027** | **= $80,492,745** |
| **Net Benefit = consequence cost – mitigation cost = $65,066,718** | | | | |

**Decision Making**

A good expert decision after all the analyses will minimize cost and maximize benefit. In this regard, making emergency response decisions when a complex system is in operation and runs into problems can be very risky or can tend far from benefit maximization. This is because, the operator may not have enough data detailing the causes of the emergency situation at hand. Therefore, the decision to mitigate any potential cause of a hazardous event to the lowest minimum from design and construction is well recommended as it will ensure the uninterrupted performance of the system to a reasonable extent. This risk management tactic is known as the **Design-Out Management**.

The Cost Benefit Analysis of the events that can create a Capsizing Hazard offshore has been solved. The overall cost of feasible response actions to minimize the risks were summed as the "cost of mitigation" and evaluated **$15,426,027** while the cost of damage resulting from the uncontrolled risks whose consequence is Capsizing is **$80,492,745**. With this, the net cost benefit of controlling a large volume of the risks through proper design and construction is a whooping sum of **$65,066,718.**

Hence, in a reliable and safe working condition, continued benefits are projected to outweigh costs, therefore, controlling these risks in the design and construction phases is the most appropriate decision.

## UNCERTAINTY REGARDING THE ROOT CAUSE OF CAPSIZING OF JACK-UPS

Wherever uncertainties exists, there is a high risk of failure. According to *Sue Wygant et al., 2007*, a root cause is the deepest fundamental cause or causes of negative or positive symptoms within any process of which if made to disappear, would result in a substantial reduction or elimination of a major event. In this case, our symptoms are negative - corrosion, installation error, structural fatigue, etc., and our major event is unwanted and catastrophic - Capsizing.

## ROOT CAUSE ANALYSIS

To identify the root cause of capsizing, we will analyze the jack-ups that has failed by capsizing. In doing this, we will consider a sample of 14 incidents.

| Jack-up rig identities | Year of incident | Description of the Cause | Contributing factors |
|---|---|---|---|
| 1. Sea Gem | 1965 | Material failure | a. Corrosion<br>b. Temperature changes<br>c. Cyclic loadings on legs (fatigue) |
| 2. Ocean Express | 1976 | Vessel stability | a. Weather condition<br>b. Installation error |
| 3. Gemini | 1974 | Material failure | a. Fatigue on structural legs |
| 4. Bohai 2 | 1979 | Collapsed during tow | a. Installation error<br>b. Severe weather condition |
| 5. NAGA-7 | 2021 | Punch-through/leg penetrated the soil | a. Seabed foundation failure |
| 6. Mr. Bice | 1998 | Material failure | a. Structural fatigue<br>b. flooding |
| 7. Rowan Gorilla I | 1988 | Material failure | a. Structural fatigue<br>b. Bad weather |
| 8. Maersk Victory | 1996 | Punch-through | a. Seabed foundation failure |
| 9. Al Mariyah | 2006 | Material failure | a. Corrosion<br>a. fatigue |
| 10. Baku 2 | 1976 | Punch-through | a. Seabed foundation failure |
| 11. Roger Buttin 3 | 1966 | Legs penetrated faster than jacking | a. Seabed foundation failure |
| 12. Dixilyn Field 83 | 1986 | Material failure/starboard leg broke through during preloading at 4m air gap | a. Fatigue on legs – corrosion fatigue and stress |
| 13. Perro Negro 6 | 2013 | Punch-through: collapsed seabed caused tilting of the rig and consequent hull damage | a. Seabed foundation failure |
| 14. Kolskaya | 2011 | Collapsed under tow | a. Fierce storm |

**Table 3.** Sample of capsized jack-up incidents

The contributing factors are the conditions or situations that increased the chances or likelihood of the capsizing. Using the ***Fishbone Diagram*** to analyze the general contributing factors.

**FISHBONE DIAGRAM**

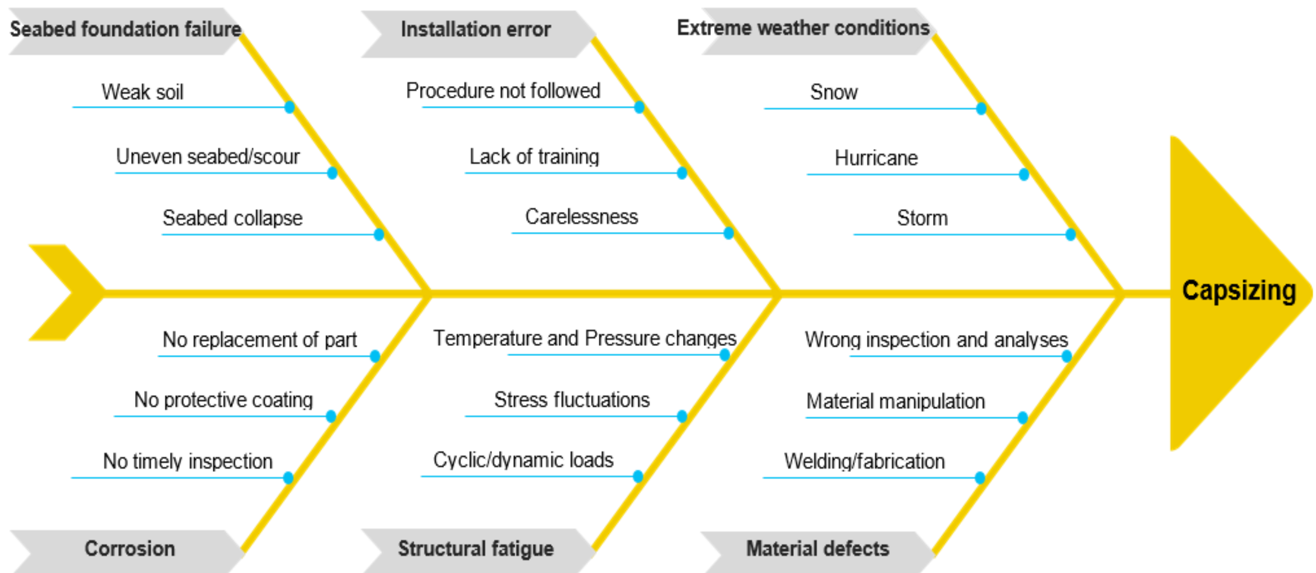


**Figure 6.** Root cause analysis using Fishbone Diagram technique

**Material defects** caused by welding/fabrication, wrong inspection analyses, and material manipulation. In the ocean environment, it exists mainly because there are limited tools that can produce requisite results or information of the material without basing on assumptions. These assumptions makes it difficult to correctly assess or affects the chance of detecting defects in a particular material, and limits the chance of correctly sizing the defects. For optimal inspection, it is important to develop methods to accurately quantify the chance of detecting flaws and the correct sizing of the defects. Worth mentioning is that there is, in the meantime, no adequate procedures or methods for inspection in the offshore environment that accounts for defects introduced in materials by marine growth.

**Installation error** caused by lack of training of personnel, not following procedures and carelessness exists due to poor knowledge of safety management. Before installation, installers must be trained to prioritize safety and understand the implications of a single error. Currently, designs does not assess the effects of human error and the effects of accidental loads platforms. Hence, installers not adequately trained to minimize errors are time bombs.

**Extreme weather conditions** such as hurricane winds, snow and storm which affects the ocean environment are natural. These conditions becomes an additional load on the structure and stirs waves with uncertain horizontal load magnitude. The only means to adequately define these random ocean waves is through probabilistic methods and statistics. In reducing the impact of extreme weather conditions, there is need to develop sophisticated models which will be used to define and evaluate the expected maximum winds, waves, snow, storms and currents expected at specified time intervals on the jack-up platform and the response of the platform to these loads in that environment.

**Structural fatigue** caused by cyclic loads, stress fluctuations and temperature changes in structural parts exists because there are no techniques developed for the realistic assessment of material characteristics such as yield, toughness, fatigue strength, and corrosion rate in the ocean environment.

**Seabed foundation failure** is caused by weak soil, uneven seabed/scour, and seabed collapse. To abate this, before installation, the soil foundation must be surveyed and its capacity known. This area requires major attention, and an appropriate model for predicting collapse need to be developed. Approximations with respect to the true or real behavior of the jack-up under bending and tension forces/loads at each candidate site have to be checked. Hurricane loads significantly contributes to punching, therefore, with the absence of methods to properly describe what happens at the foundation and joints under such an environmental load, seabed slide and collapse may not stop. Also, improper evaluations of the capacity of the platform contributes to foundation collapse when the platform is overloaded.

**Corrosion** which is an electrochemical process occurs in the presence of moisture and oxygen. This simultaneous action of moisture and oxygen oxidizes the iron (Fe) in steel to produce rust. This rust is approximated to occupy six times of the original material's (steel) volume.

*Equation:* $Fe + 3O_2 + 2H_2O = 2Fe_2O_3H_2O$
(Steel) + (Oxygen) + (Water) = Hydrated ferric oxide (Rust).

The rate at which the process of corrosion progresses is dependent on some factors of which the principal factor is the surrounding or environment. In ocean environment, corrosion of steel structural parts is natural and expected. Therefore, lack of timely inspection, protective coating and/or replacement of structural steel part, especially the underwater parts like the legs or hull leads to jack-ups capsizing under corrosion fatigue. On parts that are above the water level, crevice corrosion can occur at welded joints or on surface steel through surface debris. Inspections, protective coatings and replacements are solutions to avert corrosion fatigue which leads to capsizing.

**Comment:** From the above analyses and observations, the authors have inferred that the main cause of capsizing of jack-ups is more of procedural failure.

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**Measures to substantially control or make the contributing factors disappear**

1. Methods, analyses and frameworks that will help in the management of organization and human errors which plays an important role when it comes to the reliability of the jack-up system need to be well defined and implemented.
2. Practical methods for the realistic characterization of the dependability or reliability of the assembled structural elements of jack-up structures including the effects of the harsh ocean environment need to be defined.
3. Practical methods for the realistic characterization of the loadings and demands being placed on jack-up structures need to be defined.
4. Uncertainties such as data, measurement and modeling uncertainties; and organization-human actions uncertainties need to be defined, characterized and analyzed effectively.
5. A 'capsizing of jack-ups' structural reliability analysis format which will allow the implementation of full-scope and life-cycle reliability methods in new jack-up systems need to be developed and defined.
6. Practical ways and procedures which can lead to elucidation and definition of suitable, worthy, acceptable and/or tolerable reliability of jack-up structures in the ocean environment need to be defined.
7. The interaction between the jack-up structure foundation and soil need to be realistically defined.

## GENERAL RECOMMENDATIONS AND IMPROVEMENTS

1. Formal risk assessment technologies need to be adopted for the jack-up production facility design and operation.
2. Risk analysts should use finite element software tools to perform consequence analyses. However, there is need for finite element software to be improved to include an ocean environment domain where the environments can have variety of soil foundation parameters as well as the various extreme weather and sea states conditions plus their load impacts on jack-ups. This is very important when considering the stability of jack-ups, and it will help in improving the actual knowledge of capsize mechanism in a real-world environment.
3. Design guidelines and risk management on the various design aspects, operations and on human errors should be well developed.
4. Offshore safety cases should particularly include assessment of the risks associated with jack-ups in the offshore environment with a quantified risk assessment for a major hazard such as the Capsizing Hazard.

## CONCLUSION

The offshore accident reviews revealed that jack-ups have failed more than any other type of offshore structure in the offshore environment and that a significant number of them failed by capsizing which often results to deaths of crew members, damage of the jack-up and pollution of the environment by the release of hydrocarbons into the sea. However, there has been confusion or uncertainties in ascertaining the root causes of capsizing of jack-ups. The Formal Safety Assessment (FSA) was adopted in this paper and the Fault Tree Analysis (FTA) risk assessment technique was used to quantify the probability jack-ups capsizing through the risk factors.

The FTA result showed that without mitigating the risks of threats, that in continuous use and non-repairable condition, the jack-up have a high chance of failing prematurely even before reaching the minimum design life of 10 years. It also indicated that if the risks of the threats are reduced, that the survival probability of the jack-up would increase for the minimum time and that serious inspection and repairs can commence after the minimum time.

Using the Fishbone Diagram – a technique for determining the root cause of a problem; from the sampled accident cases, fatigues (corrosion and load induced fatigues) were present in almost every incident case with a material failure, and absent in accidents which occurred during towing. Installation errors and weather conditions were present in cases of platform instability, while foundation failures and extreme weather conditions were increasingly responsible for legs penetrating the soil. After analyzing the individual contributing factors, the analyses solved the perplexing problem of the predominant cause of jack-ups capsizing and the results distinctively pointed at procedural failures. Controlling strategies to substantially arrest or reduce Capsizing were issued and it includes defining and developing practical methods and procedures that will be realistically considered during design and put to practical use during fabrication, installation and in-service operation.

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