A RELIABLE PROCEDURE FOR LOAD COEFFICIENT DETERMINATION IN STRUCTURAL RELIABILITY ASSESSMENT OF AGEING OFFSHORE PLATFORMS

EZANIZAM BIN MAT SOOM

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Razak Faculty of Technology and Informatics
Universiti Teknologi Malaysia

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To my beloved wife, family, lecturers and friends

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ABSTRACT

Most of the oil and gas jacket platforms in Malaysia have exceeded their design life span with various underwater structural irregularities. Through the bow-tie risk assessment approach, it is predicted that there could be potential threats of hazard due to the unreliable procedure used to determine the load coefficient (α) value which could contribute to the failure in structure caused by extreme wave-in-deck. This issue is attributed to the unreliable procedure used to determine a load coefficient (α) value for wave height maximum limit (H_{RSR}) at $limiting\ RSR$ value in limit state equation. In practice, a range of 1.7 to 2.0 of load coefficient (α) value of 1.7 is recommended for practical application without considering an alternative reliable procedure to determine the appropriate values for a specific location and type of structure. In addition, the current practice to determine the appropriate load coefficient (α) value is by site measurement monitoring which is very costly and inefficient for offshore works. The study herein aims to develop a new alternative reliable procedure for load coefficient (α) determination, particularly for structural reliability assessment of ageing offshore oil and gas jacket platforms. A risk-based assessment (RBA) has been widely practised by the industry and it is based on the design code for fixed offshore structures that utilize the probabilistic model approach on load model (wave load) and load strength (load resistance) of limit state equation. Global Ultimate Strength Assessment (GUSA), which has been developed by PETRONAS, is one of the methods used in the study to compare the probability of failure (POF) and return period (RP) against ISO 19902. The results demonstrate that the most reliable procedure of load coefficient (α) range from 1.7 to 2.1 with eight (8) percent in coefficient of variance (COV) for the load model method. The accurate load coefficient (α) value was determined by the structure's experiencing wave loading by at least two (2) prescribed return period (RP) at the long-term probability distribution. The ratio between the proposed and standard practice of load coefficient (α) was determined and evaluated for the platforms studied. In this study, a comparison between standard practice and the proposed reliable procedures indicates that the standard procedure systematically overestimate the structural probability of failure (POF) by up to 74 percent. Meanwhile, the return period (RP) is significantly underestimated by the standard practice at five (5) times lower than the proposed procedure. Results also indicate that the structure configuration, subsidence effect and extreme water level influence the selection of load coefficient (α) value. The results generated comply with the standard compliance of value delivery and classification of benefits to the platform operator and thus, are beneficial economically in terms of resources optimisation and platform's reassessment.

ABSTRAK

Kebanyakan pelantar jaket di Malaysia telah melebihi had limit reka bentuk, termasuk keadaan struktur di bawah air. Dijangkakan dalam pendekatan risiko penilaian bow-tie, potensi ancaman bahaya adalah prosedur yang tidak tepat untuk menentukan nilai pekali beban (α) yang mengakibatkan kegagalan struktur disebabkan oleh paras air yang melampau. Ini berkaitan dengan ketidakpastian kaedah untuk menentukan nilai pekali beban pada had ketinggian ombak maksimum (H_{RSR}) ditetapkan untuk kadar $limit\ RSR$ bagi persamaan had. Secara praktikal, beban nilai pekali (α) dalam lingkungan 1.7 hingga 2.0 digunakan untuk perairan di Malaysia. Walau bagaimanapun, beban nilai pekali (α) 1.7 disyorkan untuk penggunaan praktikal tanpa kaedah alternatif bagi menentukan nilai sesuai pada lokasi tertentu dan jenis struktur. Di samping itu, secara praktisnya untuk menentukan nilai pekali beban (α) yang sesuai adalah dengan pemerhatian di lapangan yang mana memerlukan kos yang tinggi dan tidak efisien untuk kerja-kerja luar pesisir. Kajian di sini bertujuan untuk membangunkan satu kaedah baru yang efisien bagi menentukan nilai pekali beban (α), terutama untuk struktur luar pesisir tetap sedia ada. Penilaian berasaskan risiko (RBA) telah diamalkan secara meluas oleh industri dan berdasarkan kod reka bentuk untuk struktur luar pesisir tetap, yang menggunakan pendekatan model kebarangkalian pada model beban (beban ombak) dan kekuatan beban (rintangan beban) pada persamaan keadaan had. Salah satu kaedah penilaian risiko (RBA) yang digunakan ialah Penilaian Kekuatan Tertinggi Global (GUSA), yang dibangunkan oleh PETRONAS yang akan digunakan sebagai perbandingan antara kebarangkalian kegagalan (POF) dan tempoh berulang (RP) berdasarkan ISO 19902. Hasil kajian menunjukkan bahawa lingkungan pekali beban yang terbaik (α) adalah antara 1.7 hingga 2.1 dengan lapan (8) peratus pekali varians (COV) untuk model beban. Nilai pekali beban (α) akhir ditentukan dengan sekurang-kurangnya struktur mengalami beban ombak sebanyak dua (2) tempoh berulang (RP) yang ditetapkan pada taburan kebarangkalian jangka panjang. Nisbah antara pekali beban yang dicadangkan dan standard (α) telah ditentukan dan dinilai untuk beberapa pelantar ujian. Dalam kajian ini, perbandingan antara pematuhan standard praktis dan prosedur yang boleh dipercayai menunjukkan bahawa pematuhan standard secara sistematik dianggarkan terlebih pada nilai kebarangkalian kegagalan (POF) sehingga 74 peratus. Sementara itu, tempoh berulang di bawah anggaran pada pematuhan standard dengan 5 kali lebih rendah daripada prosedur yang dicadangkan. Selain itu, hasil kajian menunjukkan bahawa struktur konfigurasi, kesan penenggelaman dan paras air yang melampau mempengaruhi pemilihan pekali nilai beban. Keputusan yang dihasilkan adalah di bawah pematuhan standard penghasilan nilai dan klasifikasi manfaat kepada operator untuk manafaat ekonomi dari segi pengoptimuman sumber daya dan penilaian semula pelantar.

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LIST OF ABBREVIATIONS

ALARP	-	As low as reasonably practicable
API	-	American Petroleum Institute
BS	-	Base shear
COV	-	Coefficient of variance
CPP	-	Central processing and production platforms
DNV	-	Det Norske Veritas
FORM	-	First order reliability method
GUSA	-	Global Ultimate Strength Assessment
HSSE	-	Health, safety, security and environment
ISO	-	International organization for standardization
LRFD	-	Load and resistance factor design
MSL	-	Mean sea level
NORSOK	-	The Norwegian shelf's sompetitive position standard
PCSB	-	PETRONAS Carigali Sdn. Bhd.
PDF	-	Probability density function
PMO	-	Peninsular Malaysia Operation
POF	-	Probability of failure
PSC	-	Production sharing contract
QRA	-	Quantified risk assessment
RBDA	-	Reliability Based Design and Assessment
RSR	-	Reserve strength ratio
RP	-	Return period
SACS	-	Structural analysis computer software
SBO	-	Sabah Operation
SESAM	-	Super element structural analysis modules
SKO	-	Sarawak Operation
SRA	-	Structural reliability analysis

SSB	-	Sarawak Shell Berhad
SSRA	-	Simplified structural reliability analysis
TOS	-	Top of steel
UFO	-	User-friendly format
USFOS	-	Ultimate strength for offshore structures
WHP	-	Wellhead platform
WSD	-	Working stress design

LIST OF SYMBOLS

B	-	Factor of Model Uncertainty on the Resistance
B_D	-	Bias of Dead Load
B_E	-	Bias of Environmental Load
B_M	-	Bias of the Environmental Load Prediction Model
B_R	-	Bias of Resistance
c	-	Load Coefficient Equal to 1 for Fixed Structures
D	-	Dead Load
D_C	-	Characteristic Load Effect
E_{100}	-	Environmental Loading for 100 years Return Period
E_c	-	Characteristic Load Effect from Environmental Load
f	-	Base Shear or Environmental Load
f_d	-	Design Load
$f_{D/E}$	-	Dead Load to Environment Ratio
F	-	Annual Extreme Lateral Load
g	-	Safety Margin
g_{mean}	-	Mean of Safety Margin
H	-	Annual Extreme Wave Height
h_1	-	Wave Heights for 1 year Return Period
h_c	-	Wave Heights for 100 year Return Period
h	-	Wave Height
h_d	-	Design Wave Height (H_{max})
HAT	-	High Astronomical Tide
H_{crest}	-	Wave Crest
H_{RSR}	-	Wave Height Maximum Limit

$H_{RSR}\ limiting$	-	Maximum Wave Height at RSR
$H_{s\ drag}$	-	Height Wave Height Significant
$H_{s\ inertia}$	-	Low Wave Height Significant
LAT	-	Low Astronomical Tide
$limiting\ RSR$	-	RSR is Limited to H_{RSR} at Cellar Deck
$In\ R$	-	Lognormal Distribution for Resistance
$In\ Q$	-	Lognormal Distribution for Load
P_f	-	Failure Function
POF	-	Probability of Failure
R	-	Resistance or Strength Model
R'	-	Probabilistic of Ultimate Strength
R_i	-	Characteristic Resistance
R_{mean}	-	Mean Collapse Strength
RSR	-	Reserve Strength Ratio
Q	-	Load Model
Q_c	-	Characteristic Design Wave-Current Load
Q_1	-	Characteristic 1 year Wave-Current Load
$Q_{w,c}$	-	Characteristic Design Wind Load
$Q_{w,1}$	-	Characteristic 1 year Design Wind Load
V_1	-	Wind Speed for 1 year Return Period
V_c	-	Wind Speed for 100 year Return Period
V_D	-	COV of Dead Load
V_E	-	COV of Environmental Load
V_Q	-	COV for Load
V_R	-	COV for Resistance
α	-	Load Coefficient
β	-	(Annual) Reliability Index
$\beta\sigma_g$	-	Reliability for Standard Deviation
γ_D	-	Dead Load Factor
γ_E	-	Environmental Load Factor
δ_H	-	COV for Annual Extreme Wave Height
δ_Γ	-	COV for Uncertainty Factor in Estimating the Wave Load

δ_F	-	COV for Annual Extreme Lateral Load
ξ	-	Uncertainty of the Collapse Resistance of the Structure or Factor Introduced to Measure for the Model Uncertainty in the Resistance
μ_R	-	Mean of Resistance Model
μ_Q	-	Mean of Load Model
Φ	-	Cumulative Frequency Distribution
ϕ_i	-	Resistance Factor
T_R	-	Notional Return Period
σ_R	-	Standard Deviation of Resistance
σ_Q	-	Standard Deviation of Load
σ_g	-	Standard Deviation of Safety Margin
Γ	-	Analysis Uncertainty Factor in Estimating the Wave Load

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CHAPTER 1

INTRODUCTION

1.1 Background

The oil and gas industry in Malaysia began in the early 1900s and has evolved over 115 years. The first onshore oil well, known as Miri Land Field, was discovered at Miri Sarawak in December 1910. Offshore exploration began in Sarawak in 1961 with the discovery of more oil and gas fields including Patricia, Temana and West Lutong by Sarawak Shell Berhad. In 1974, Petroleum National Berhad (PETRONAS) took over the oil and gas industry on behalf of the Malaysian Government under Petroleum Development Act 1974 (Narayanan and Mohd Akram, 2009). In 1976, production-sharing contract (PSC) agreement was made between PETRONAS and Sarawak Shell Berhad/Sabah Shell Berhad.

In recent years, the energy sector, specifically in oil and gas, is facing challenges as the resources are declining (Rabah *et al.*, 2017; Gerhard, 2015). Moreover, the rising development costs and an increase in the demand for oil and gas has pressured companies to improve their recovery of oil and gas resources from developed fields and to develop discovery reserves from existing oil and gas platforms. This approach has resulted in significant reduction in development costs, resulting in good project economics and the ability to recover more oil and gas resources (Goh, 1999). Additionally, youthful economic exuberance has now given way to middle-aged restraint, leading to the reduction in the price of oil and rise in the field-development and operating costs. It should be noted that leveraging on the existing facility to process production from a newly discovered field may lead to an effective development option.

In the late 1990s, reliability engineering has become a common practice in the Malaysian oil and gas industry in order to assess the integrity and requalification of offshore platform. There are more than one hundred and ninety-one installation (191) platforms with fixed-type offshore structures in Malaysia (Twomey, 2010). The fixed-type offshore structures, known as fixed jacket platforms, are commonly used in oil and gas production in the shallow water depths of Malaysia. Currently, the offshore operation available is Peninsular Malaysia Operation (PMO), the Sarawak Operation (SKO) and the Sabah Operation (SBO). Majority of platform types include wellhead, drilling, production, gas compression, living quarters, vents and risers. However, the platform structures have exceeded their design life (Shuhud, 2008).

1.1.1 Ageing of Fixed Offshore Structures and Its Challenges

Over a 20 year period, a total of one hundred and ninety-one (191) installations have been in operation, of which 65% of the platforms have been in operation for 25 years or more, operating beyond their initial design life of 20 to 25 years. A report in 2014 indicated that ageing of the existing installation will increase to 78% in another five years (Ayob *et al.*, 2014b; Narayanan and Mohd Akram, 2009). As continuous production is required beyond the design life, life extension of the installations is inevitable. Table 1.1 tabulates the installation age distribution of offshore platforms in the region of Malaysian waters.

Table 1.1: Platform age distribution

Platform age	No of Platform	Percentage (%)
≥ 25	124	65
20 - 24	25	13
10 - 19	18	9
< 10	24	13
Total	191	100

Ayub *et al.* (2014b)

Offshore fixed jacket platforms are widely used in a majority of offshore platforms in Malaysia. The selection of a fixed jacket platform is based on the shallow water depth, design impact, reservoir trajectory, drilling approach and production capacity (Bai, 2003). The fixed jacket platform such as wellhead platform (WHP) or satellite platform is intended for the drilling of production wells in which the design is suited for the type of drilling rig, either jack-up or tender-assisted rig. In addition, the bigger and integrated fixed jacket platforms normally intended for house living quarters and production systems are known as a central processing and production (CPP) platforms.

A fixed jacket platform is divided into two sections where the first section, i.e. the upper part, is known as the topside and the second section, i.e. the bottom part, is known as the substructure. The conventional offshore fixed jacket platform for offshore consists mainly of a substructure (a vertical section made of tubular steel supported by driven piles and anchored directly to the seabed – also known as a jacket) with a deck placed on top, providing space for crew living quarters, a drilling rig and production facilities. Figure 1.1 shows the main components of a conventional offshore fixed platform.

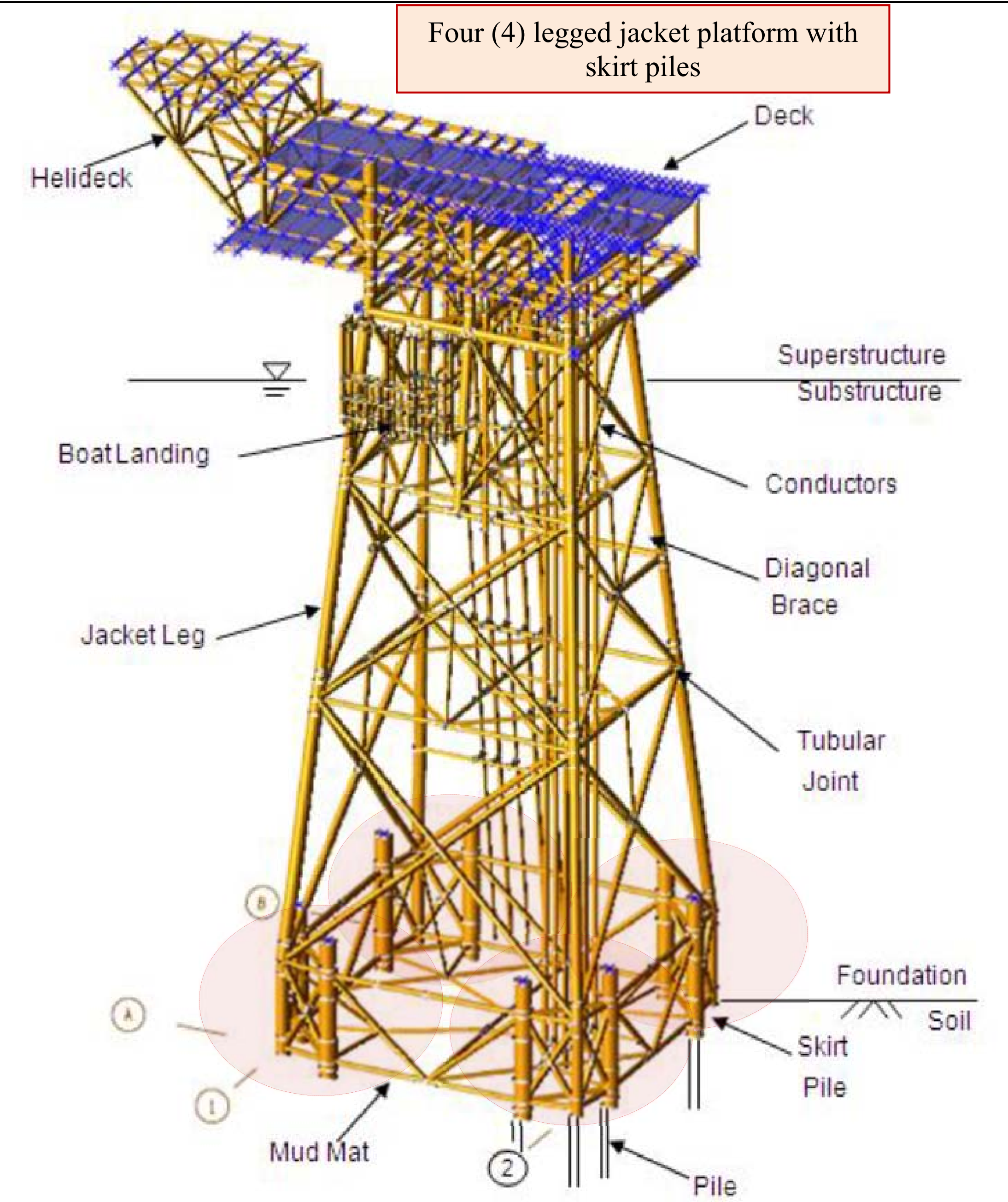

Figure 1.1: Conventional offshore steel fixed platform.

PETRONAS Carigali (2012)

The topside is an important element that houses all the production skids and the working deck. The upper part is located above the water level or at mean sea level (MSL), while the substructure is located underwater on the seabed with leg piles which provide support for the foundation piles, conductors, risers and other appurtenances. An axial force is transferred from the structure and topsides into piles at the top of the structure.

Major modifications and fatigue concerns have led to significant changes to platform loading issues of structural integrity and reliability. Hence, it is necessary to perform an evaluation of possible life extension of ageing platforms where structure failure is expected when the strength capacity is unable to resist the applied load. Additionally, the structural failure can stop production before the limit of platform life or decommission (API, 2000).

Based on the reservoir capacity and current technology, the existing offshore structures in Malaysia are commonly designed for 25 to 30 years design life. However, as a result of deeper drilling explorations and techniques, current technological advancements enable identification of more reserves by the operator and production-sharing contract (PSC).

Space limitation and structural integrity of the existing platforms have resulted in limitations in the recovery of oil and gas. It is clear that structural integrity is one of the major issues for ageing and existing platforms, particularly during major modifications and occurrence of fatigue problem among the jacket members. A study demonstrated that insufficient strength and an excessive load are the common causes of ageing of offshore structure platforms (Ayob *et al*., 2014b). Insufficient load is defined as a source of error in design, fabrication, installation or operation and degradation, while excessive load is referred to environment, operation and accidental.

Evidence has shown that the modifications of offshore structure platforms lead to higher loading, which the platform opposes from its original design and capacity (Nicholas *et al*., 2006). Furthermore, several studies have also demonstrated the reliability of Malaysian jacket platforms (Nor Azman, 2011; Kurian, *et al*., 2012) and other types of platforms available across the world (Shabakhty, 2004; Rajasankar *et al*., 2003; Onoufriou and Forbes, 2001). The studies attempted to demonstrate the fitness for the purpose of the structure and to define the optimum mitigation measures.

It should be noted that the main goal of studies is to demonstrate the structural reliability assessment: a rational method of putting the economics and engineering of offshore structures to understand the uncertainties, particularly those connected with severe ocean storms (Shell Research, 1993).

1.2 Risk Assessment in Determining a Problem

Risk-based assessment (RBA) is a quantitative approach for control barrier in bow-tie process of risk assessment. Due to its proactive approach, bow-tie is considered as the best control in managing the risk of the top event or the business upset event. Bow-tie model is a powerful tool for communicating hazards and their control. Moreover, bow-tie is a health, safety, security and environment (HSSE) tool that supports ‘as low as reasonably practicable’ (ALARP). ALARP is commonly used by oil and gas company to evaluate and manage the risk. ALARP is defined as the point at which the costs (in time, money and effort) of further risk reduction is grossly disproportionate to the risk reduction achieved (Buijsingh, 2013). Furthermore, a safer approach to risk management is a method that attempts to prevent or eliminate hazards or reduce the magnitude, severity or likelihood of occurrences by careful attention to the fundamental design and layout.

Top event is the first event of an incident which include near miss and accident. Bow-tie is divided into two main sections; on the left side of the top event are threat control measures, while on the right side of the top event are recovery measures. First, the threat control measures will be identified based on the occurrence of listed threats which are originated from the identified hazard. In contrast, the recovery measures will be determined as recovery preparedness to reduce and or eliminate consequences of the top event. Figure 1.2 shows bow-tie diagram problem. Definition of each element in bow-tie are as follows:

i) Hazard is known as anything that has potential to cause harm to people, asset, environment and reputation.

ii) A threat is an action that can cause the top event to occur or which hazard could be released.

iii) Control barrier is an action to stop the threat from occurring or prevent the hazard from being released.

iv) Top event is the first event of an incident which includes a near miss and accident which prevent the hazard from being released.

v) Recovery barrier is any action taken to reduce the occurrence of consequence

vi) Consequence is the result of hazard being released, and is related to people, asset, environment and reputation. The consequence can lead to minor or major damage.

As shown in the developed bow-tie diagram for this study (Figure 1.2), changes in global weather which can lead to the seabed subsidence due to reservoir compaction and variable in metocean data are identified as a hazard. Moreover, wave-in-deck has been attributed to air-gap extinction, which has been identified as the top event. Hence, based on the principal of bow-tie methodology, it was found that the threat of the hazard is an inaccurate procedure to determine the load coefficient (α) value. Furthermore, risk-based assessment element as control barrier is applied to determine a reliable procedure for load coefficient determination and is validated by conducting parametric studies of load coefficient. This is needed to prevent the top event. On the other hand, applying recovery barrier, which is a retroactive approach, can only reduce the impacts and consequences of a catastrophic event. Figure 1.3 shows an example of consequence of structural failure due to extreme environmental overload during Hurricane Lily in The Gulf of Mexico.

Metocean data is derived from hindcast data which may not represent natural climate variability due to the nature of unpredictable weather on some occasions. Hindcast data is a prediction process in which a length of periods or duration data are measured, especially for long-term data. Furthermore, normal approach hindcast data may come from neighbouring area provided both sites satisfy similar condition criteria (ISO, 2005). The changes in the increment of metocean data may result in significant impact to platform clearance or air gap balance height. The impact to the offshore structure may be severe in the presence of unexpected rare events of wave, wind, current and storm surge.

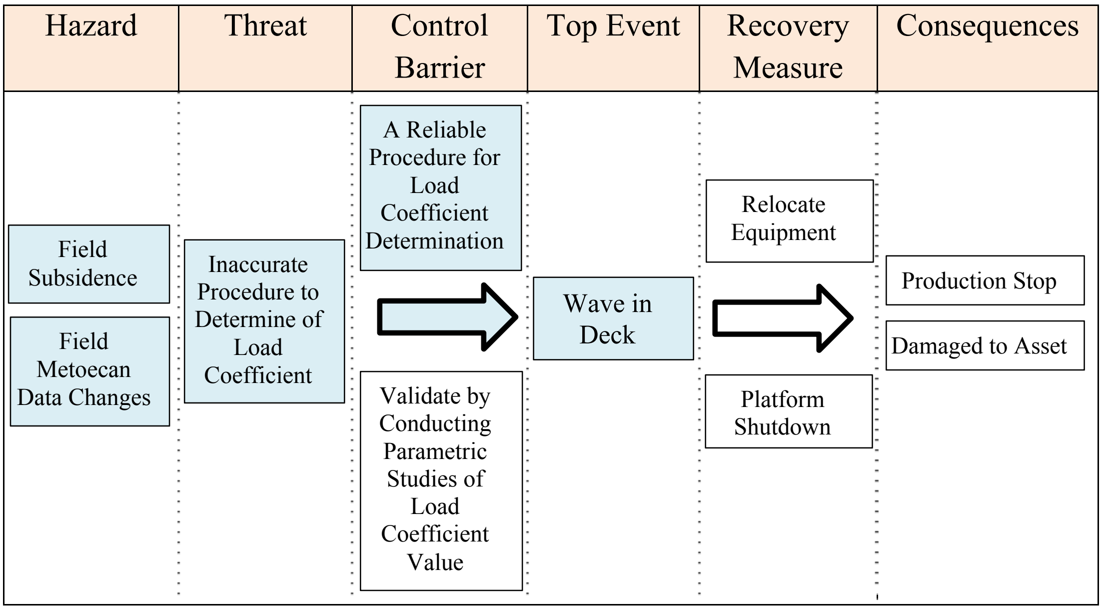

Figure 1.2: Bow-tie to problem statement

Figure 1.3: Hurricane Lily's impact on fixed platform

Shell Group of Companies (2013)

1.3 Problem Statement

There is a growing number of ageing offshore structures in South China Sea water. The ageing structures are comprised of various underwater structure anomalies, such as joint crack, member flooding, shallow gas, subsidence, fish bombing, etc. (Ayob *et al.*, 2014b). Despite the demand to prolong production and their service lifetime, issues of the deterioration of structural integrity and probability of platform structures to collapse have been reported as the offshore structures are exposed to complex and extreme environmental conditions during their lifetime.

Wave-in-deck force is one of the main factors linked to structural integrity. Wave-in-deck force occurs when inundation of water affected the lowest deck (i.e. cellar deck) in which old and newly installed platform structures are affected. The wave collapse point level to be above the cellar deck level by giving (-) negative value. Many factors contribute to wave-in-deck, such as seabed subsidence and occurrence of extreme environmental conditions as shown in Figure 1.4. The above factors are caused by inaccurate prediction during initial design resulted from the absence of accurate data. Therefore, air-gap is crucial during design stage itself as it allows accurate prediction of deck vertical clearance between the highest water surface elevation that occurs during extreme metocean conditions and the underside of cellar deck level.

The wave-in-deck level at the platform is shown in Figure 1.5. The recent wave-in-deck level (+/-) for the platform is represented as the difference between cellar deck level (critical deck) and extreme water level. $Limiting\ RSR$ is where reserve strength ratio (RSR) is limited to be referred for H_{RSR} at cellar deck. Maximum limit wave height at reserve strength ratio or normally called as H_{RSR}. $H_{RSR}$from the result of ultimate strength for offshore structure (USFOS) software and H_{max} for any prescribed return period (RP). Return period means the expected number of characteristic load to occur only once in that year (Srinivasan, 2016).). It should be noted that sufficient air-gap and the impact load is critical in predicting the performance of the platform structures under an extreme environment where H_{max} or H_{RSR} is less than or exceed the cellar deck.

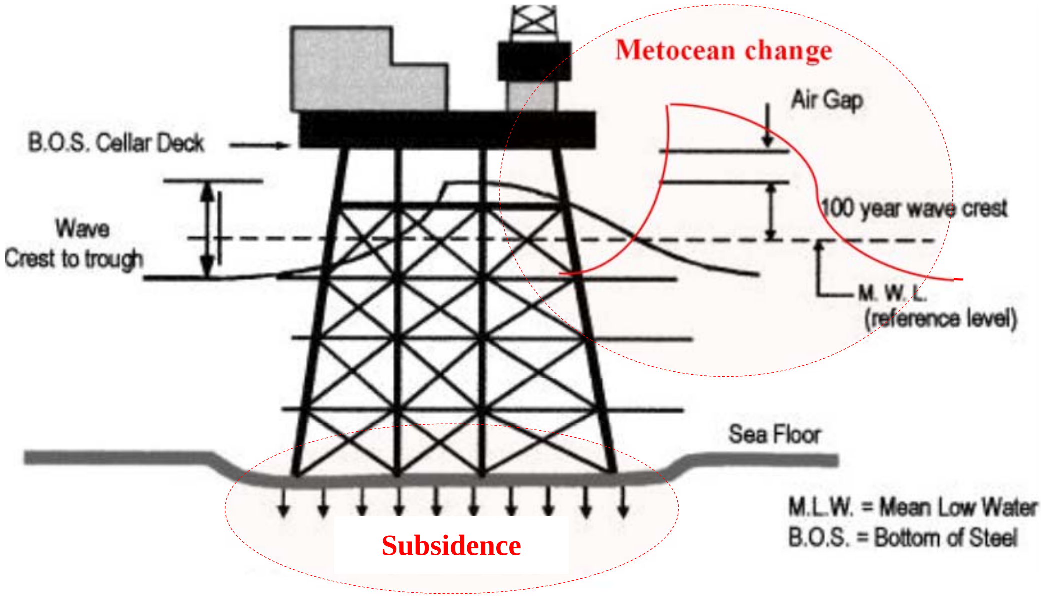

Figure 1.4: Elements (hazard) contribute to problem

Source form public domain

Insufficient air gap clearance between the mean sea level (MSL) to the lowest deck can cause disastrous effects as shown in Figure 1.6. This is because the wave-in-deck impact an offshore platform during extreme weather, which leads to damage to the topside deck structure and overall or global collapse.

Currently, in industry practice, operators invest large amounts of capital for equipment deployment and offshore site measurements, which can reach RM100K per day for three (3) or more months duration in order to get the accurate data for predicting the correct wave height of H_{RSR} and wave in-deck.

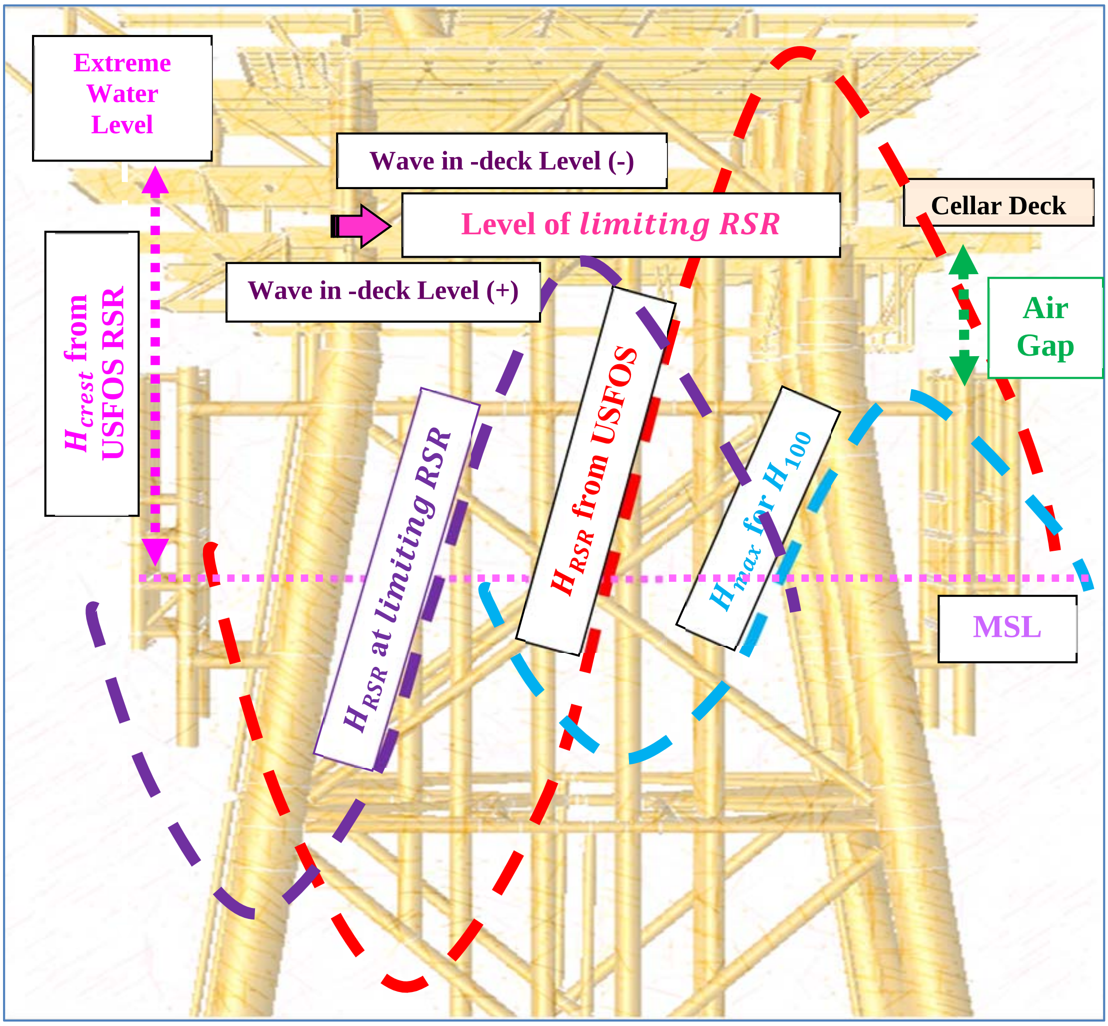

Figure 1.5: Illustration of H_{RSR}, $limiting\ RSR$ and wave-in-deck

Sample 3D view from SACS model

Figure 1.6: Actual photos of wave-in-deck loading scenario

Shell Group of Companies. (2013)

The maximum limit wave height (H_{RSR}) and $limiting\ RSR$ can be measured by using limit state equation which is based on the probabilistic model approach. In limit state equation, one (1) of the uncertainty parameters is load coefficient (α) and it is referred to as base shear (BS) values measured for different wave height and return period (RP) that produce the collapse load (Kurian *et al.*, 2013; DE and E & P, 1995; Gerhard *et al.*, 2003). Currently, the load coefficient values used to determine the H_{RSR} at $limiting\ RSR$ of platform structures in Malaysian waters are based on the oil and gas operator standard practice approach. It was demonstrated that in common practice, PETRONAS Carigali Sdn Bhd (PCSB) uses a load coefficient value in the range of 1.7 to 2.0. Nonetheless, a load coefficient value of 1.7 is recommended by Metocean Department of PCSB as a conservative approach that is limited by validity in terms of replication in research as the value is only used in industrial practice judgement (Goh, 1999). Hence, a reliable load coefficient procedure for a specific location and structure is essential to be ascertained, as optimised design and resources may contribute to better field economics.

1.4 Aim and Objectives

The study aimed to develop a reliable procedure for load coefficient (α) determination in structural reliability assessment of ageing offshore platforms installed under extreme storm loading. To achieve the main objective as above, the following objectives were pursued in this study:

i) To **assess** the recent development and **investigate** the current industry practice in structural reliability analysis procedure for fixed offshore structures

ii) To **develop** a reliable procedure for load coefficient determination in structural reliability assessment

iii) To **validate** the new load coefficient value by conducting parametric studies.

1.5 Scope of Study

The study will cover the structural reliability analysis for fixed offshore structures in the Sabah and Sarawak regions. All platforms and environmental data are provided by Sarawak Shell Berhad (SSB). In this study, the structural reliability analysis, i.e. Global Ultimate Strength Assessment (GUSA) procedure, was used for the structural probability of failure (POF) and $limiting\ RSR$ as common practice in the industry. All figures, tables, text and diagrams are significantly modified when compared to the original. It should be noted that utilisation of ageing platforms is the application of this study.

This study performed the quantitative risk assessment which is used to calculate the structural reliability analysis. The main focus of this study is to obtain the values risk estimates, such as reserve strength ratio and base shear and the probability distributions of the return period. The method of risk-based assessment for structural reliability analysis application in this study is the GUSA.

The five (5) platforms to be tested were selected based on the assessments focusing on global impact towards the platform due to major environmental loading and impact subsidence issue. The model substructure or jacket for fixed offshore structures was identified as those using either a tripod, a four and eight-legged structure with different water depths, ranging from 25m to 130m from mean sea level (MSL). The age of platforms is between 15 – 37 years old.

The environmental condition input data is omnidirectional and return period applied for the region or area is 100-year from original design and align with standard ISO 19902 and API WSD; initial/original design for linear analysis is 100-years. For non-linear analysis and for long term distribution response to extreme and abnormal metocean parameters, additional of 1000-year and 10000-year are recommended in order for the platform to experience certain wave period before collapse.

1.6 Significance of Study

Deployment of the instrument equipment and measured at the site offshore were those used in the oil and gas industry. As the price of oil and gas has decreased it is neither cost-effective or efficient for operator to conduct this approach even though it was more accurate procedure based on site monitoring (offshore). Hence, application of risk-based assessment has become an instrument for continuous improvement and optimization to industry to evaluate result through analysis and formulation. In Malaysia waters, the application of Global Ultimate Strength Assessment (GUSA) and Risk-Based Design and Assessment (RBDA) will be useful to access the integrity and reliability of existing structures.

The load coefficient (α), which is structural reliability analysis, is important to determine the collapse point of fixed offshore structures based on reserve strength ratio and H_{RSR}. The current study is expected to introduce and develop a reliable procedure for load coefficient determination in structural reliability analysis of ageing offshore platforms. The procedure is aimed at improving the range of load coefficient values with statistical approach method. Current practice (α =1.7) leads to underestimation of the probability of failure and reserve strength ratio values. Additionally, a reliable procedure is required to determine load coefficient value from at least two (2) times offshore structure experience wave loading as per prescribed return period.

The study expected to demonstrate application to limit state equation from the probabilistic model (load and resistance) as part of H_{RSR}, reserve strength ratio and maximum wave (H_{max}) at region. Verification of maximum wave crest with measurement of wave breaking crest limit and an assessment of the wave in deck level condition at each field and platform will be performed in specific locations as mentioned previously.

An accurate load coefficient value leads to higher confidence level on design, reduced cost on future site monitoring and recovery measure (if disastrous occurs). The study outcomes are expected to assist the operator as part of production- sharing contract (PSC) in decision-making and outline action items as part of their business risk management.

1.7 Thesis Outline

Chapter 1 discuss the general background of the ageing fixed offshore structure with their challenge and major issue condition. In view of risk assessment in determining a problem. Detail of problem statement. Continue with aim and objective in order to solve the problem. Scope of study and significance of study. The thesis outline for each chapter is described.

Chapter 2 demonstrates the general background of structural reliability analysis including development, criteria (deterministic, semi-probabilistic and probabilistic), principles (demand and supply), quantified risk assessment (i.e. bow-tie) in conjunction with structural reliability analysis and structural reliability analysis procedures for oil and gas industry in Malaysia. GUSA, reserve strength ratio, non-linear plastic collapse, type of failure mechanism, simplified structural reliability analysis (SSRA), standard bias and coefficient of variance (COV), extreme air gap and ISO 19902 requirements are also described. In view of load model versus strength (resistance) model under Stochastic process and how it is related to limit state equation of probabilistic model. The chapter also describes the principle of load coefficient value for uncertainty of COV of load model, wave breaking, delivery and classification of benefit.

Chapter 3 demonstrates the research methodology in detail including research flowchart, introduces overall GUSA procedures with numerical example i.e. from step 1 to step 5 such as analysis and assessment of design global in place for linear analysis, conditional assessment, the model analysis in Sesam (GeniE), model result from ultimate strength for offshore structure (USFOS) software and simplified structural reliability analysis. The selection basis of different type of platform to be tested and a detailed explanation of the development of a reliable procedure for load coefficient determination, identification of the load coefficient range, load coefficient values selection by proposed of a reliable procedure with numerical example are also described. Brief of validation process for new load coefficient.

Chapter 4 describes the effect of load coefficient on probability of failure, return period, extreme water level and wave in-deck. The chapter also discusses the evaluation of the GUSA for the ultimate maximum force of reserve strength ratio and base shear, mode of failure for test structures and ultimate maximum force for simplified structural reliability analysis. Determination of load coefficient is based on a reliable procedure for average plotting graph. In addition, this chapter includes validation of proposed load coefficient, ratio comparison for the probability of failure and return period and discussion of overall analysis and assessment. A brief explanation of the value delivery and classification of benefit for selected platforms are also included in this chapter.

Chapter 5 concludes with each study objective. A brief description of contribution, novelty and implication related to the theoretical, knowledge, practical and methodology aspect is presented. Several recommendations for future work are also addressed in this chapter under the limitation of findings and recommendation.

REFERENCES

Abu Husain, M. K., Mohd Zaki, N. I., Mallahzadeh, H. and Najafian, G.(2014), *Short-term Probability Distribution of the Extreme Values of Offshore Structural Response by an Efficient Time Simulation Technique*. UTM: Ships and Offshore Structures Journal, 10, pp. 1-12.

Anthony, P.P., Paul, K.Y., Paul, R.C. (1997). *Effect of Design, Fabrication and Installation on Structural Reliability of Offshore Platforms.* Houston: Offshore Technology Conference.

API (2000). *American Petroleum Institute - Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms – Working Stress Design RP 2A-WSD (Twenty-First Edition). Errata and Supplement 1 (Dec 2002), 2 (Sept 2005) & 3 (Aug 2007).* New York: API Publishing Services.

Arangio, S. (2012). *Int. J. Lifecycle Performance Engineering, Vol. 1.* Italy: Sapienza University of Rome.

Ayob, M. S., Kajuputra, A. E., Mukherjee, K. B. and Wong, S. (2014a). *Global Ultimate Strength Assessment for Existing Offshore Jacket Structures*. PETRONAS: OTC-24938-MS.

Ayob, M. S., Kajuputra, A. E., Mukherjee, K. B. and Wong, S. (2014b). *Requalification of Offshore Jacket Structures in Malaysia Waters*. PETRONAS: OTC-25021-MS.

Azman, N. U., Abu Husain, M. K., Mohd Zaki, N. I. and Mat Soom, E. (2017). *The Effect of Wave-in-deck in Conventional Pushover Analysis.* Nantes, France: VII International Conference on Computational Methods in Marine Engineering (MARINE).

Bai, Y. (2003). *Marine Structural Design.* Houston, USA: Elsevier Ltd

Bea, R. G. and Mortazavi, M. (1992). *Experimental Validation of ULSEA with Results from Frame Tests*. Honolulu, Hawaii: 7th International Offshore and Polar Engineering Conference (ISOPE)

Benjamin, J. R. and Cornell, C. A. (1970*), Probability, Statistics and Decision for Civil Engineers*. McGraw-Hill

Bentley (2013). *Structural Analysis Computer Software*. SACS IV Manual. Version 7.0. Revision 2.

Birkinshaw, M. and Smith, D. (1996). *The Setting of Target Safety Levels for the Assessment of offshore Structures.* Los Angeles: 6th International Offshore and Polar Engineering Conference (ISOPE). Volume IV, pp 447-456.

Boon, M. Si., Vanderschuren, L., Van de Graaf , J. W. and Tromans, P. S. (1993). *Failure Probability of Southern North Sea Platform Under Environmental Loading.* Singapore: Proceedings if the Third International Offshore and Polar Engineering Conference (ISOPE).

Buijsingh, P. (2013). *ALARP Guide,* Houston, Shell

Chakrabarti, S. K. (2005). *Handbook of Offshore Engineering. Vol 1.* USA: Elsevier Ltd. Illinois,

Chanakya, A. (2009). *Design of Structural Elements. Third Edition.* NY, USA: Spon Press.

Cornell, C. A. and Krawinkler, H. (2000). *Progress and Challenges in Seismic Performance Assessment*. PEER Center News.

David Brown, F. and William Dun, E. (2007). *Application of Quantitative Risk Assessment Methodn to Emergency Response.* Computers and Operations Research, 34, 1243-1265

DE, R. S. and E & P Technology Company (1995). *Risk Analysis Methodology for Developing Design and Assessment Criteria for Fixed Offshore Structure.* Houston, USA: OTC 7755

DeCoursey, W. J. (2003). *Statistic and Probability for Engineering Application.* University of Saskatchewan.

DNV (1996). *Guideline for Offshore Structural Reliability Analysis – Application to Jackets.* HØvik, Norway: Report No. 95-3203, Rev 01, Det Norske Veritas

DNV-GL (2016). *SESAM GeniE for Fixed Structures.* User Software: Norway: DNV

Dziubinski, M., Fratczak, M. and Markowski, AS. (2006). *Aspect of Risk Analysis Associated with Major Failures of Fuel Pipeliness.* Journal of Loss Prevention in the Process Industries, 19, 399-400

Efthymiou, M. and Van de Graaf, J. W. (1997). *Reliability Based Design and Reassessment of Fixed Steel Platforms, SIEP 97-5050*. Houston, Shell

Efthymiou, M., Wee, T. Y., Forristall, G. Z. and Graham, C. G. (1998). *Structural Integrity of the Forcados CLP Offshore Nigeria. EP 987-5686,* Nigeria, Shell

Efthymiou, M. and Van de Graaf, J. W. (2011). *Reliability and (Re)Assessment of Fixed Steel Platforms,* Rotterdam, The Netherlands: Proceedings of the ASME 30th International Conference on Ocean, Offshore and Arctic Engineering (OMAE).

Fayazi, A. and Aghakouchak, A. (2015). *Reliability Based Assessment of Existing Fixed Offshore Platforms Located in the Persian Gulf.* Tarbiat Modares University: International Journal Maritime Technology.

Gerhard, E., John, D. S. and Ivar, L. (2003). *Updating of Structural Failure Probability Based on Experienced Wave Loading.* Hawaii: Proceedings of the Thirteenth, International Offshore and Polar Engineering Conference (ISOPE).

Gerhard, T. and Alexander, N. (2015). *The Relationship Between Oil Price and Costs in the Oil and Gas Industry*. A Oxford Centre for the Analysis of Resource Rich Economies, Department of Economics, University of Oxford.

Goh, T. K. (1999). *Structural Integrity and Inspection Analyses of Old Jackets Reassessment Basis*, *Part 1. Revision 01.* PETRONAS

Hagen, Ø., Johannessen, T. B. and Berg, JØ. B. (2016). *Airgap and Wave in Deck Impact Statistic.* Busan, South Korea*:* Proceedings of the ASME 35rd International Conference on Ocean, Offshore and Arctic Engineering (OMAE).

Johannessen, T. B. and Hagen, Ø. (2016). *Characteristic Levels of Stringly Nonlinear Extreme Wave Load Effects.* Busan, South Korea*:* Proceedings of the ASME 35rd International Conference on Ocean, Offshore and Arctic Engineering (OMAE).

ISO (2005). *International Organization for Standardization - Petroleum and Natural Gas Industries – Specific Requirement for Offshore Structures. ISO 19901-1. 2005*. Switzerland: HIS

ISO (2007). *International Organization for Standardization - Petroleum and Natural Gas Industries – Fixed Steel Offshore Structures. ISO 19902. 2007*. Switzerland: HIS

ISO (2010). *International Organization for Standardization - Petroleum and Natural Gas Industries – Arctic Offshore Structures. ISO 19906. 2010*. Switzerland: HIS

Jalayer, F. (203). *Direct Probabilistic Analysis; Implementing Non-Linear Dynamic Assessment.* Stanford University: Ph.D. Thesis (CA, 244)

Karadeniz, H. (2013). *Stochastic Analysis of Offshore Steel Structures, An Analytical Appraisal.* Verlag London: Springer.

Kurian, V. J., Nizamani, Z. and Liew, M. S. (2012). *Failure Probabilities for Jacket Platform Subjected to Wave and Current.* Malaysia: Proceedings of the International Conference on Civil, Offshore and Environmental Engineering.

Kurian, V. J., Nizamani, Z. and Liew, M. S. (2013). *Bayesian Updating for Probability of Failure of Jacket Platforms in Malaysia.* IEEE Business Engineering and Industrial Applications Colloquium (BEIAC).

Kurian, V. J., Wahab, M. M. A., Kheang, T. S. and Liew, M. S. (2014a). *System Reliability of Existing Jacket Platform in Malaysia Water (Failure Path and System Reliability Index.* Switzerland: Applied Mechanics and Materials Vol. 567, pp 307-312

Kurian, V. J., Goh, S. S., Wahab, M. M. A., and Liew, M. S. (2014b) *Reliability Assessment Model for Aging Jacket Structures in Malaysia.* Switzerland: Applied Mechanics and Materials Vol. 567 (2014) pp 283-288 @ (2014).

Kurian, V. J., Goh, S. S., Wahab, M. M. A., and Liew, M. S. (2015). *Component Reliability Assessment of Offshore Jacket Platforms*. Research Journal of Applied Sciences, Engineering and Technology 9(1): 1-10.

Jamaluddin, M. A., Liew, M. S. and Kurian, V. J. (2014). *Response of monopod Platform Under Extreme Wave in Malaysia Water.* Switzerland: Applied Mechanics and Materials Vol. 567 (2014) pp 295-300 @ (2014)

Manuel, L., Schmucker, D. G., Cornell, C. A. and Carballo, J. C. (1998). A Reliability-Based Design Format for Jacket Platforms Under Wave Loads. Marine Structures Vol. 11; 413-428.

Mat Soom, E., Abu Husain, M. K., Mohd Zaki, N. I., Mohd Nor, M. N. K. and Ayob, M. S. (2015). *Global Ultimate Strength Assessment (GUSA) for Lifetime Extension of Ageing Offshore Structures.* , Hawaii, USA: Proceedings of the Twenty-Fifth International Ocean and Polar Engineering Conference on Civil, Offshore and Environmental Engineering (ISOPE).

Mat Soom, E., Abu Husain, M. K., Mohd Zaki, N. I., Azman, N. U. and Najafian, G. (2016). *Reliability-Based Design and Assessment for Lifetime Extension of Ageing Offshore Structures.* Busan, South Korea*:* Proceedings of the ASME 35rd International Conference on Ocean, Offshore and Arctic Engineering (OMAE)

Mat Soom, E., Abu Husain, M. K., Mohd Zaki, N. I., Azman, N. U., Zakiyuddin, A. and Najafian, G. (2017). *Comparison Methods for Derivation of the Failure Probability of Fixed Offshore Structures.* Shenzhen, China*:* International Conference on Ships and Offshore Structures (ICSOS).

McIntosh, A. R. and Birkinshaw, M. (1992). *The Offshore Safety Case: Structural Safety Considerations.* London: International on Structural Design Against Accidental Loads – As Part of the Offshore Safety Case. Volume 1, pp 1-8.

McCool, J. I. (2000). *Using the Weibull Distribution.* USA: A John Wiley & Sons, Inc. Publication. Wiley Series in probability and statistic. Chap. 1, page 1

Minitab 16 (2010). *Reliability Analysis.* USA: State College. Manual

Moehle, J. P. and Deierlein, G. G. (2004). *A Framework Methodology for Performance Based Earthquake Engineering.* Vancouver, Canada: 13th World Conference on Earthquake Engineering.

Moses, F. (1989). *A Global Approach for Reliability Based Offshore Platform Codes.* Ohio, USA: Case Western Reserve University.

Moses, F. and Stahl, B. (1979). *Reliability Analysis Format for Offshore Structures*. Society of Petroleum Engineers: Journal of Petroleum Technology.

Mukhlas, N. A., Abdullah Shuhaimy, N., Johari, M. B., Mat Soom, E., Mohd Zaki, N. I. and Abu Husain, M. K. (2016), *Design and Analysis of Fixed Offshore Structure - An Overview.* Universiti Teknologi Malaysia: Malaysia Journal of Civil Engineering, Faculty Civil Engineering, Vol. 28 No 3

Narayanan, S. P. and Mohd Akram, M. K. (2009). *Structural Integrity Management for Fixed Offshore Platforms in Malaysia.* World Academy of Science, Engineering and Technology International Journal of Civil, Environmental, Structural, Construction and Architectural Engineering Vol:3, No:10, 2009

Narayanan, S. P., Mohd Akram, M. K. and Khamidi, M. F. (2012). *Risk – Based Assessment in Malaysia's Offshore Jacket Platform.* Malaysian Journal of Civil Engineering 24(1):29-47 (2012).

Narayanan, S. P. and Ahmad Fawwaz, A. S. (2013). *Ultimate Strength Assessment for Fixed Steel Offshore Platform*. UTP, Malaysia: Malaysia Journal of Civil Engineering 25(2):128-153(2013)

Naresh, C. S. (2007). *LRFD for Substructures Concept of failure and Reliability Index.* Canada: NCS Consultant, LLC: #01-0607-RO

Naresh, C. S. (2012). *Using @Risk in Load and Resistance Factor Design (LRFD) Approach for Civil Engineering.* USA: NCS Consultant. Palisade Websat

Nelson, J. C., Narayanan, S. P., Idrus, A., Abdul Hamid, M. F. and Nizamani, Z. (2012). *Reliability Analysis of Jacket Platforms in Malaysia – Environmental Load Factors.* Research Journal of Applied Sciences, Engineering and Tecnology 4(19): 3544-35551, 2012.

Nicholas, N. W., Goh, T. K. and Bahar, H. (2006). *Managing Structural Integrity for Aging Platform*. Adelaide, Australia*:* Proceedings of the SPE Asia Pacific Oil and Gas Conference and Exhibition.

Nizamani, Z., Kurian, V. J. and Liew, M. S. (2014). *Determination of Environmental Load Factors for IS0 19902 Code in Offshore Malaysia using FORM Structural Reliability Method.* Journal -Ocean Engineering 92(2016) 31-43

Nordal, H. (1990). *Application of Ultimate Strength Analysis in Design of Offshore Structural Systems.* Glasgow, Scotland: 4th International Sysposium on Integrity of Offshore Structures. Pp 153-165.

Nor Azman, M. F. (2011). *Sensitivity Study of Environmental Load to Reliability Index for Malaysian Region*. Universiti Teknologi PETRONAS, Malaysia: M.Sc Thesis.

Onoufriou, T. and Forbes, V. J. (2001). *Developments in Structural System Reliability Assessments of Fixed Steel Offshore Platforms*, *Reliability Engineering System Safety.* Elsevier, 71, pg. 189-199.

Papworth, F. and Gehlen, C. (2016). *National and International Code Based Deterministic and Full Probabilistic Modelling to Describe Reliability of Various Australasian Merina Structures.* Capr Town; fib Symposium.

Paul, A. F. (2005). *Structural Reliability Analysis and limit State Design. Lecture 1, Introduction to Reliability Theory.* UK: Civil and Structural engineering Group, PCSB.

Paul, E. H., Daniel, B., Ibarahim, A. A. and Bilal, M. A. (2002). *Uncertainties in Material Strength, Geometric and Load Variables.* Naval Engineers Journal.

Shell Sdn Bhd (2012). *Guideline for Engineering Notes on the Design Fixed Offshore Structure.* PETT1: PETRONAS.

Phillips, J. J. (2003). *Return on Investment in Training and Performance Improvement Programmes,* Burlington. MA, pg. 12-13.

Pueksap-anan, P. (2010). *Sensitivity Study for RSR of Fixed Offshore Steel Type Platforms,* Asian Institute of Technology, Thailand: Msc Thesis.

Rabah, A., Zoltan, J., Douglas, L., Akito, M., Armen, N., Hou, W. and Jiaxiong, Y. (2017). *Oil Prices and Global Economy.* International Monetary Fund (IMF).

Rajasankar, J., Iyer, N. R. and Appa Rao, T. V. S. R. (2003). *Structural Integrity Assessment of Offshore Tubular Joints Based on Reliability Analysis*. International Journal of Fatigue. Elsevier.

Robert, E. M. (1999). *Structural Reliability Analysis and Prediction.* University Textbook. England: British Library Cataloguing in Publication Data.

Rutten, J. G., Van Gelder, P. H. A. J. M., Ewans, K.C. and Efthymiou, M. (2004). *Uncertainties in Extreme Value Analysis and Their Effect on Load Factors.* British Columbia, Canada: Proceedings of the ASME 35rd International Conference on Ocean, Offshore and Arctic Engineering (OMAE).

Shuhud, I. M. (2008). *Decommissioning: A Malaysian Overview*. *Regional Guidelines for Decommissioning and Removal of Platforms*. Denpasar, Indonesia: ASCOPE Workshop

Shell Research, Rijswijk. (1993). *Special Issue – The Reliability of Offshore Structures.* UK: Advance in EP Research.

Shell Group of Companies. (2013). *Integrity and Life Extension of Offshore Structures – SR.13.10667.* UK: Advance in EP Research.

Shell Exploration and Production Company (1995). *Risk Analysis Methodology for Developing Design and Assessment of Fixed Steel Platforms.* UK: Advance in EP Research.

Shabakhty, N. (2004). *Durable Reliability of Jackup Platforms – The Impact of Fatigue, Fracture and Effect of Extreme Environmental Loads on the Structural Reliability*. T.U. Delft Netherlands: Ph.D. Thesis.

SINTEF Group (2001). *USFOS Getting Started*. Marintek, Structural Engineering.

Smith, D. and Birkinshaw, M. (1996). *The Extreme Weather Hazard – Airgap Determination.* London: ERA Conference – Offshore Structure, Hazard and Inetgrity Management. Volume 7, Part 1, pp 1-10

Spouge, J. (1999). *A Guide to Quantitative Risk Assessment for Offshore Installation.* Norway: The Centre for Marine and Petroleum Technology.

Srinivasan, C. (2016). *Offshore Structural Engineering, Reliaibility and Risk Assessment.* London and New York: Taylor and Francis Group.

Svein, F. and DNV (1978). *Reliability of Offshore Structure*. Society of Petroleum Engineers of AIME: Journal of Petroleum Technology.

Thoft-Christensen, P. and Murotsu, Y. (1986). *Application of Structural Systems Reliability Theory.* Heidelberg: Springer – Verlag Berlin

Trahair, N. S., Bradford, M. A. and Nethercot, D. A. (2001). *The Behaviour and Design of Steel Structures to BS5950.* New York: Spoon Press

Twomey, B. (2010). *Study Assess Asia-Pacific Offshore Decommissioning Costs*. *Oil & Gas Journal*.

Vanderschuren, L., Efthymiou, M., Tromans, P. S. and Van de Graaf, J. W. (1996). *Reliability of a Jacket Structures in a Tropical Cyclone Environment.* Florence: 15th International Conference on Offshore Mechanics and Arctic Engineering (OMAE). Volume II, pp 1366-1374.

Van de Graaf, J. W., Tromas, P. S. and Efthymiou, M. (1994). *The Reliability of Offshore Structure and Its Dependence On Design Code and Environment.* Houston: 26th Annual Offshore Technology Conference. Paper No. OTC 7382

Van de Graaf, J. W., Tromas, P. S., Vanderschuren, L. and Jukui, B. H. (1996). *Failure Probability of a Jack-Up Under Environmental Loading in The Central North Sea.* Marine Strutures (Journal), Volumes 9, Part 1, pp 3-24. Elsevier Science.

Walker, J., Murphy, E., Ciardulli, F., and Hamm, L. (2014). *On The Reliance on Modelled Wave Data in The Arabian Gulf for Coastal and Port Engineering Design.* Artelia Gulf, Dubai, United Arab Emirates.

Zaghloul, H. (2008). *Calibration of Deterministic Parameters for Reassessment of Offshore Platforms in the Arabian Gulf Using Reliability-Based Method.* University of Western Australia: Ph.D. Thesis.