MODIFIED RELIABILITY REASSESSMENT OF FIXED OFFSHORE STRUCTURES FOR MALAYSIAN WATER

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Dedicated to my beloved family for their unfailing support

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ABSTRACT

Fixed offshore platform structures are subjected to external loadings such as gravity loads, environmental loads, hydrodynamic loads and accidental loads. The structures continuously undergo modifications and upgrading in order to meet safety and production demands or due to structural damage on critical components. The aim of this research is to propose an improved Structural Reliability Assessment (SRA) methodology for fixed offshore platforms in Malaysian waters by including the effect of wave-in-deck and to quantify the impact of key design parameters on overall platform structural response. Case studies on the sensitivity of marine growth profile, current blockage factor, drag and inertia coefficients on overall structural loading are performed to quantify the overall impact of these key parameters. The platform reliability based on proposed improved method is compared against an existing method, the Simplified Structural Reliability Assessment (SSRA). For the case and sensitivity studies, the examples of existing fixed offshore jacket structures in Malaysian water region are used. In structural integrity assessment of existing platforms, structural utilization factor is used to measure the level of stress on structural members and foundation. The study on structural integrity assessment shows that the drag coefficient and current blockage factor have significant impact on the overall loading of jacket structures in Malaysian waters as compared to marine growth profile and inertia coefficient. The sensitivity study on drag coefficient quantifies the percentage increases on base shear for operating and storm conditions, ranging from 17% to 72% and 18% to 70% respectively. The current blockage factor sensitivity study for operating and storm conditions shows the base shear increase from 10% to 16% and 6% to 9% respectively. The existing platforms may not be able to meet today's integrity requirement without performing costly strengthening. Therefore, a modified SRA method is proposed to demonstrate the fit-for-purpose of the platforms based on As Low As Reasonably Practical (ALARP) concept which has been proven to be a cost effective solution to non-compliant existing and ageing platforms. The advantage of the method is its ability to estimate the magnitude of wave height that causes platform failure and takes into consideration the wave-in-deck in the calculation of platform Reserve Strength Ratio (RSR). The study demonstrates that including additional loading contribution from wave-in-deck in the RSR calculation is more practical, realistic and accurate. The case study demonstrates the platform RSR decreases from 4.13 to 3.40 which is equivalent to 17% reduction. In the final phase, this study proposes a unique parameter Alpha, (α) which is used to calculate the wave height that causes platforms to collapse. The α depends on platform geometrical configuration. The sensitivity study concludes the values of α for fixed offshore structures at Malaysian water ranging from.1.5 to 2.5.

ABSTRAK

Struktur pelantar tetap luar persisir sentiasa terdedah kepada berbagai daya luaran seperti daya graviti, alam sekitar, hidrodinamik and kemalangan. Struktur ini sentiasa melalui proses pengubahsuaian dan naiktaraf untuk memenuhi keperluan keselamatan, pengeluaran minyak dan gas atau disebabkan oleh kerosakan komponen kritikal struktur tersebut. Objektif utama penyelidikan ini adalah untuk mencadangkan kaedah baru dalam Penilaian Kebolehpercayaan Struktur *(SRA)* untuk pelantar tetap luar persisir perairan Malaysia dengan mengambil kira gelombang pada dek pelantar dan juga menyukat kesan perubahan parameter utama rekabentuk pelantar. Kajian kes kepekaan pertumbuhan marin, faktor hadangan arus, pekali seretan dan inersia terhadap keseluruhan daya tindakan ke atas struktur pelantar dilakukan untuk mengukur kesan keseluruhan parameter utama tersebut. Pengiraan kebolehpercayaan struktur pelantar yang menggunakan metodologi tambahbaik yang dicadangkan akan dibandingkan dengan kaedah sediada, Penilaian Mudah Kebolehpercayaan Struktur *(SSRA)*. Contoh struktur pelantar yang digunakan adalah daripada pelantar yang beroperasi di persisir laut Malaysia. Dalam penilaian integriti struktur pelantar sediada, faktor penggunaan struktur digunakan untuk mengukur aras ketinggian tegasan di dalam komponen struktur serta cerucuk struktur. Kajian penilaian integriti struktur menunjukkan pekali seretan dan hadangan arus mempunyai kesan signifikan kepada daya tindakan keseluruhan ke atas struktur berbanding dengan profil pertumbuhan marin dan pekali inersia. Kajian kepekaan ke atas pekali seretan memberi peratusan kenaikan daya ricih asas untuk keadaan operasi dan ribut, masing-masing adalah sebanyak 17% hingga 72% dan 18% hingga 70%. Kajian kepekaan terhadap faktor hadangan arus ketika keadaan operasi dan ribut menunjukkan peningkatan daya ricih asas, masing-masing sebanyak 10% hingga 16% dan 6% hingga 9%. Pelantar luar persisir sediada berkemungkinan tidak dapat memenuhi keperluan integriti masakini jika pengukuhan struktur yang mahal tidak dijalankan. Oleh itu, kaedah penambahbaikan *SRA* yang dicadangkan akan dapat membuktikan rekabentuk *fit-for-purpose* berteraskan konsep Serendah Munasabah DiPraktikan (*ALARP)*. Konsep *ALARP* telah terbukti menjadi penyelesaian kos efektif terhadap pelantar sediada dan lama yang tidak mematuhi kod. Kebaikan kaedah baru *SRA* yang dicadangkan adalah ia berupaya menganggar magnitud ketinggian gelombang yang menyebabkan struktur pelantar runtuh dan seterusnya mengambil kira gelombang pada dek dalam pengiraan Nisbah Kekuatan Simpanan *(RSR)*. Kajian menunjukkan dengan mengambil kira gelombang pada dek pelantar dalam pengiraan *RSR* adalah lebih praktikal, realistik dan tepat. Keputusan kajian menunjukkan *RSR* pelantar menurun dari 4.13 ke 3.40 iaitu sebanyak 17%. Dalam fasa terakhir, penyelidikan ini mencadangkan parameter *Alpha*, (α) yang digunakan untuk mengira ketinggian gelombang yang menyebabkan struktur pelantar runtuh. Parameter α bergantung kepada bentuk geometri pelantar. Kajian kepekaan merumuskan nilai α yang bersesuaian untuk pelantar luar persisir di perairan Malaysia adalah dalam lingkungan 1.5 sehingga 2.5.

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LIST OF ABBREVIATIONS

AISC	-	American Institution of Steel Construction
ALARP	-	As Low as Reasonably Practicable
API	-	American Petroleum Institute
BOS	-	Bottom of Steel Elevation
BS	-	Base Shear
Calm	-	Calm Sea Condition
CB	-	Control Buoy
CS	-	Calm Sea Condition
CPT	-	Cone Penetration Test
DAF	-	Dynamic Amplification Factor
DATAGEN	-	Data Generator
DEP	-	Design Engineering Practice
DNV	-	Det Norske Veritas
EDI	-	Engineering Dynamic Corporation
EL	-	Elevation
FPS	-	Floating Production Storage
FPSO	-	Floating Production Storage and Offloading
HAT	-	Highest Atronomical Tide
ISO	-	International Organization for Standardization
JONSWAP	-	Joint North Sea Wave Project
KC	-	Keulagen-Carpenter Number
LAT	-	Lowest Atronomical Tide
LRFD	-	Load and Resistance Factor Design
LCOMB	-	Load Combination
MDOF	-	Multiple Degree of Freedom
MSF	-	Module Support Frame
MSL	-	Mean Sea Level

Norsok	-	Norwegian Standard
O.D.	-	Outer Diameter
OGP	-	Oil and Gas Producer
OM	-	Operating Mooring
OP	-	Operating Maximum Topside
OPB	-	Out-of-Plane Bending
OPER	-	Operating Condition
OPR	-	Operating Condition
OTM	-	Overturning Moment
PCSB	-	Petronas Carigali Sdn. Bhd.
PETRONAS	-	Petroliam Nasional Berhad
PM	-	Pierson-Moskowitz
RP	-	Recommended Practice
RSR	-	Reserve Strength Ratio
SACS	-	Structural Analysis Computer System
SC7	-	Subcommittee 7
SDOF	-	Single Degree of Freedom
SES	-	Standard Engineering Specification
SESAM	-	Super Element Structural Analysis Method
SMEP	-	Shell Malaysia Exploration and Production
S_{max}	-	Storm Condition with Maximum Loading
S_{min}	-	Storm Condition with Minimum Loading
SRA	-	Structural Reliability Assessment
SSRA	-	Simplified Structural Reliability Assessment
ST	-	Storm Maximum Topside
STORM	-	Storm Condition
SX	-	Storm Minimum Topside
TC	-	Technical Committee
TLP	-	Tension Leg Platform
TSA	-	Thermal Spray Aluminum
TTP	-	Through Thickness Properties
UC	-	Unity Check
USA	-	United States of America
USFOS	-	Ultimate Strength for Offshore Strucuture

UFO	-	User Friendly Format
VLAP	-	Very Low Abandonment Project
WSD	-	Working Stress Design
WT	-	Wall Thickness

LIST OF SYMBOLS

A	-	Area of object
A_{BF}	-	Projected area of each individual member that obstruct current flow
A_{ch}	-	Variable for combined axial tension, bending and hydrostatic pressure
A_j	-	Variable for joint check
A_n	-	Projected area normal to the cylinder axis per unit length
A_{PM}	-	Pierson-Moskowitz formulation variable
B_E	-	Bias of environmental load
B_m	-	Bias of the environmental load prediction model
B_{PM}	-	Pierson-Moskowitz formulation variable
B_R	-	Bias of resistance
$BOS_{cellar\ Deck}$	-	Bottom of steel elevation of cellar deck
$BS_{collapse}$	-	Platform base shear at platform collapse
A_s	-	Side surface area of pile
A_v	-	Cross sectional area for beam shear
A_{wd}	-	Area of wetted silhouette
$\bar{A}$	-	Enclosed area within the structure periphery, normal to the current flow direction
a	-	Wave amplitude
B_{ch}	-	Variable for combined axial tension, bending and hydrostatic pressure
$BS_{Dynamic}$	-	Base shear for dynamic condition
BS_{Max}	-	Maximum base shear

BS_{Static}	-	Base shear for static condition
BS_Deck	-	Total base shear due to wave just below the deck
BS_WID	-	Total base shear due to wave-in-deck
$BS_{100-yrs}$	-	Platform base shear at 100-years return period
C	-	Wave celerity or speed
C_b	-	Critical elastic buckling coefficient
C_D	-	Drag coefficient
C_{De}	-	Drag coefficient for appurtenances
C_{Dm}	-	Drag coefficient for member
C_{damp}	-	Damping value
C_h	-	Critical hoop buckling coefficient
C_m	-	Inertia coefficient
C_{me}	-	Inertia coefficient for appurtenances
C_{mm}	-	Inertia coefficient for member
C_{mx}	-	Reduction factor corresponding to member X-axis
C_{my}	-	Reduction factor corresponding to member Y-axis
C_s	-	Shape coefficient associate with the geometry / shape
C_u	-	Wave velocity, (wave length/wave period)
C_V	-	Wave celerity
C_1	-	Wave loading uncertainties on the specific jacket structure
C_2	-	Load coefficient
C_3	-	Load coefficient
C_{1s}	-	Variable for Stoke 5th order
C_{2s}	-	Variable for Stoke 5th order
CDS	-	Drag coefficient for steady-flow
c	-	Undrained shear strength of soil
c_c	-	Wave velocity in Cnoidal wave theory
D	-	Diameter of tubular
D_c	-	Outside diameter
D_{chord}	-	Chord diameter
D_e	-	Diameter of appurtenance element

D_{leg}	-	Platform leg diameter
D_m	-	Diameter of modelled member
D_{mg}	-	Cylinder diameter for circular unit length (including marine growth)
D_{mgr}	-	Overall average diameter of member including marine growth
D_n	-	Nominal inertial load
D_1	-	Self weigh of the structure
D_2	-	Weigh of equipment or other objects that change from one mode of operation to another
DAF	-	Dynamic amplification factor
DAF_{BS}	-	DAF due to base shear
DAF_{OTM}	-	DAF due to overturning moment
$Dynamic_i$	-	Peak dynamic response
d	-	Still water level
d_b	-	Diameter of brace
d_{brace}	-	Thickness of brace
d_c	-	Water depth for cnoidal wave theory
d_{CD}	-	Still water level to calculate drag coefficient
d_{mean}	-	Mean water depth
d_{p23}	-	Water depth for P23 platform
d_0	-	Reference depth for the wind generated current
d_1	-	Water depth in stick model
E	-	Young’s modulus of elasticity
E_c	-	100-year characteristic load
E_s	-	Elastic modulus
$E_{Topside}$	-	Wave-in-deck load
e	-	Surface roughness
F_{bn}	-	Nominal bending strength
F_{CB}	-	Current blockage factor
F_{cn}	-	Nominal axial compressive strength

$F_{collapse}$	-	Unfactored global environmental loading with co-existing unfactored permanent (i.e. gravity) vertical loads that cause collapse of the structure
F_D	-	Drag force
$F_D(z,t)$	-	Drag force per unit length
F_{ey}	-	Euler buckling strength corresponding to member y-axis
F_{ez}	-	Euler buckling strength corresponding to member z-axis
F_{hc}	-	Nominal critical hoop buckling strength
F_{he}	-	Elastic hoop buckling stress
F_I	-	Inertia force
$F_I(z,t)$	-	Inertia force per unit length
F_j	-	Equivalent inertia forces at j^{th} level
F_n	-	Non-dimensional coefficient in Stoke 5^{th} order
F_{vn}	-	Nominal shear strength
F_{vtn}	-	Nominal torsional strength
F_{wind}	-	Wind force
F_{wave}	-	Wave loading
$F_{wave}(z,t)$	-	Wave force per unit length
F_{xc}	-	Nominal inelastic local buckling stress
F_{xe}	-	Nominal elastic local buckling stress
F_y	-	Yield stress
F_{yb}	-	Yield strength of the brace member
F_{y_chord}	-	Yield strength of the chord member at the joint
F_{100}	-	Unfactored 100-year global environmental loading
f	-	Unit skin/shaft friction capacity
f_{AX}	-	Factored axial stress
f_b	-	Bending stress due to factored load
f_{by}	-	Bending stress about member Y-axis (in-plane) due to factored loads
f_{bx}	-	Bending stress about member Z-axis (out-of-plane) due to factored loads

f_c	-	Axial compressive stress due to factored load
f_h	-	Hoop stress due to factored hydrostatic pressure
f_{IPB}	-	Factored in-plane bending stress
f_{OPB}	-	Factored out-of-plane bending stress
f_p	-	Peak frequency
f_t	-	Axial tensile stress due to factored loads
f_v	-	Maximum shear stress due to factor loads
f_{vt}	-	Torsional shear stress due to factored loads
f'_t	-	Variable for combined axial tension, bending and hydrostatic checks
$G(f)$	-	Pierson-Moskowitz transfer function
g	-	Gravity acceleration
g_b	-	Gap between brace
H	-	Wave height
$H_{collapse}$	-	Wave height at platform collapse
H_j	-	Height of j^{th} level from mudline
H_{max}	-	Maximum wave height
H_{m0}	-	Significant seastate
H_s	-	Significant wave height
H_w	-	Wave height
H_z	-	Variable use for design hydrostatic head
$H_{100-yrs}$	-	Wave height at 100-years return period
h	-	Water depth
I	-	Moment of inertia
I_p	-	Polar moment of inertia
K	-	Effective length factor
K_b	-	Buckling factor
$K_{lateral}$	-	Coefficient of lateral earth pressure/stiffness of the system
K_{SDOF}	-	Stiffness of the system
KC	-	Keulegan-Carpenter number
k	-	Number of wave
k_c	-	Constant

k_{mgr}	-	Average peak-valley height of marine growth
k_{nl}	-	Non-linear wave number
k_s	-	Stiffness
L	-	Wave length
L_{col}	-	Length of column
L_e	-	Length of appurtenance element
L_{hoop}	-	Length of cylinder between stiffening ring, diaphragms or end connection
L_m	-	Length of modelled member
L_1	-	Live load includes weight of the consumable supplies and fluids in pipes and tanks
L_2	-	Short duration forces exerted on the structures from operation
l	-	Unbraced length
M_D	-	Factored bending moment in the brace member
$M_{inertia}$	-	Inertia bending moment
M_{max}	-	Maximum moment at the bottom of pile (measured experimentally)
M_{SDOF}	-	Mass of the system
M_{uj}	-	Ultimate joint bending moment capacity
M_{vt}	-	Torsional moment due to factored loads
m_j	-	Lump mass at j^{th} level
N	-	The order of the stream function
N_q	-	Dimensionless bearing capacity factor
n	-	Minimum order of the stream function or Stoke 5^{th} theory
n_{level}	-	Number of level in the structure
n_s	-	Total number of segments on each face of platform
$OTM_{Dynamic}$	-	Overturning moment for dynamic condition
OTM_{Static}	-	Overturning moment for static condition
P	-	Applied force
P_D	-	Factored axial load in the brace member

P_{DE}	-	Axial pile load for extreme environmental condition
P_{DO}	-	Axial pile load for operating environmental condition
P_f	-	Annual probability of failure
P_{uj}	-	Ultimate joint axial capacity
p	-	Factored hydrostatic pressure
p'_o	-	Effective overburden pressure
Q_D	-	Ultimate axial pile capacity
Q_f	-	Design factor to account for the present of longitudinal factored load in chord
Q_{fr}	-	Skin friction resistance
Q_g	-	Gap factor
Q_u	-	Ultimate strength factor
Q_p	-	Total end bearing
Q_β	-	Geometric factor
q	-	Unit end bearing capacity
R_m	-	Reynolds number
RMS_{Dyn}	-	Root mean square for dynamic condition
$RMS_{Dyn\ BS}$	-	Root mean square for dynamic condition due to base shear
$RMS_{Dyn\ OTM}$	-	Root mean square for dynamic condition due to overturning moment
RMS_{Static}	-	Root mean square for static condition
$RMS_{Static\ BS}$	-	Root mean square for static condition due to base shear
$RMS_{Static\ OTM}$	-	Root mean square for static condition due to overturning moment
RSR	-	Reserve strength ratio of the system
RSR_WID	-	Platform RSR calculated based on wave-in-deck
r	-	Radius of gyration
$r_{c/w}$	-	Current over wave velocity ratio

S	-	Elastic section modulus
S_c	-	Wave trough elevation above the bottom
$S_{PM}(f)$	-	Pierson-Moskowitz wave spectrum
$S_{response}(f)$	-	Structural response spectrum toward wave loading
S_t	-	Wave trough elevation above the bottom
$Static_i$	-	Peak static response
$Surge_{100}$	-	Strom surge at 100-year return period
s	-	Distance from seabed
T	-	Wave period
T_{app}	-	Apparent wave period
T_{app}	-	Associated period
$T_{cantilever}$	-	Natural period of the system
T_{chord}	-	Thickness for chord
T_h	-	Duration of the half wave cycle
T_n	-	Natural period of the system
T_p	-	Peak period
T_z	-	Mean zero crossing period
t	-	Thickness of tubular
t_{Aw}	-	Time in airy wave theory
t_{mgr}	-	Thickness of marine growth
t_p	-	Thickness of plate
U_c	-	Free stream current velocity
U_{cw}	-	Current speed in line with the wave
U_m	-	Maximum water particle velocity normal to the member
U_{mo}	-	Maximum horizontal particle velocity
U_{mov}	-	Maximum wave induced orbital velocity
U_s	-	Reduced current velocity
$\overline{U}(z)$	-	Mean wind speed
$\overline{U}_{ref}$	-	One hour mean wind speed taken at reference elevation, Z_{ref}

U_w	-	Fluid velocity
$U_{1hour,10m}$	-	1-hour sustained wind speed @ height 10m above sea
u	-	Horizontal water particles velocity
$u(z,t)$	-	Water particle velocity acting normal to the axis of the member
$\dot{u}$	-	Horizontal water particles acceleration
$\dot{u}(z,t)$	-	Water particle velocity acting normal to the axis of the member
V	-	Beam shear due to a factored load
$V(z')$	-	Velocity at height z above the seabed
$V_C(z)$	-	Total current velocity at elevation z
$V_c(0)$	-	Current velocity at the still water level
$V_{c,wind}(z)$	-	Wind generated current profile
$V_{c,wind}(0)$	-	Wind-generated current velocity at the still water level
V_E	-	COV of environmental load
$V_{inertia}$	-	Inertial base shear
V_I	-	Current velocity
V_{IV}	-	Current component in-line with wave
V_R	-	Covariance of resistant
V_S	-	Covariance of load
V_s	-	Velocity at the surface or MSL
v	-	Vertical water particles velocity
v_k	-	Kinematic viscosity of water
$\dot{v}$	-	Vertical water particles acceleration
W_e	-	Force applied to the structure due to combined action of extreme wave
W_o	-	Force applied to the structure due to combined wave, current and wind
w	-	Seawater density
w_{air}	-	Weight density of air
$wave\ crest_{100}$	-	Maximum crest elevation at 100-year return period

$X(n)$	-	Unknown coefficient
x	-	Horizontal position / distance
x_c	-	Horizontal position in cnoidal wave theory
Y_T	-	Water depth up to wave trough in cnoidal wave theory
y	-	Crest position in cnoidal wave theory
Z	-	Plastic section modulus
Z_{el}	-	Elevation above sea level
Z_{ref}	-	Reference elevation
Z_s	-	Stretched vertical coordinate
z	-	Vertical position / distance
z_c	-	Distance from still water level
z'	-	Elevation above seabed
α	-	Constant parameter governed by platform geometrical configuration
α_i	-	Proportionality constant
$\alpha_{inertia}$	-	Inertia force factor
β	-	Ratio of brace diameter to chord diameter
β_i	-	Proportionality constant
$\beta_{inertia}$	-	Inertia force factor
$\beta_{reliability}$	-	Reliability index
δ	-	Friction angle between soil and pile wall
$\delta_{cantilever}$	-	Displacement of the system
ϵ	-	Strain of the structural member
ϕ_b	-	Resistance factor for bending strength
ϕ_c	-	Resistance factor for axial compressive strength
ϕ_h	-	Resistance factor for hoop buckling strength
ϕ_j	-	Resistance factor for tubular joints
ϕ_t	-	Resistance factor for axial tensile strength
ϕ_q	-	Resistance factor for yield stress
ϕ_v	-	Resistance factor for shear strength
ϕ_{PE}	-	Resistance factor for extreme environmental condition

ϕ_{PO}	-	Resistance factor for operating environmental condition
γ	-	Ratio of chord diameter to two times of chord thickness
γ_D	-	Hydrostatic pressure load factor
γ_E	-	Load safety factor
η	-	Surface profile of wave
η_s	-	Water surface elevation
η_{ch}	-	Variable for combined axial tension, bending and hydrostatic checks
λ	-	Wave length
λ_j	-	Variable to calculate design factor to account for the presence of longitudinal factored load in the chord
λ_s	-	Column slenderness parameter
λ_y	-	Column slenderness parameter corresponding to member y-axis
λ_z	-	Column slenderness parameter corresponding to member x-axis
μ	-	Geometric parameter
μ_R	-	Mean strength
μ_S	-	Mean load
π	-	Pi
ρ	-	Mass density of seawater
σ	-	Stress on the structural member
τ	-	Joint geometry parameter
υ	-	Poisson’s ratio
Ω	-	Ratio of forcing frequency and natural frequency
ω	-	Circular frequency
ω_n	-	Natural frequency of the system
ω_w	-	Forcing wave frequency
ξ	-	Coefficient for DAF calculation

ψ_{soil}	-	Undrained shear strength divided by effective overburden pressure
$\emptyset_{1j}$	-	Mode shape amplitude for mode 1 at jth level
$\emptyset_{2j}$	-	Mode shape amplitude for mode 2 at jth level
$\emptyset$	-	Diameter for tubular
$\emptyset()$	-	Standard normal cumulative probability function
$\propto$	-	Power law exponent
$\propto_{soil}$	-	Dimensionless factor
$\propto_{cb}$	-	Current blockage factor for the structures
$\propto_{wk}$	-	Wave kinematic factor
$[C]$	-	Damping matrix
$[d]$	-	Displacement
$[F]$	-	Applied load
$[K]$	-	Stiffness matrix
$[K_{SDOF}]$	-	Stiffness matrix
$[M]$	-	Mass matrix of the total system
$\{x\}$	-	Displacement

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CHAPTER 1

INTRODUCTION

1.0 Development of Oil and Gas Industry in Malaysia

The oil industry in Malaysia was started as early as 1910 with the construction of the first onshore oil rig at Canadian Hill, Miri, Sarawak (Sorkhabi, 2010). In Peninsular Malaysia, the exploration activities of petroleum resources only started back in late 1960s on the east Peninsular Malaysia namely offshore Terengganu and Kelantan.

Up-to-date there are about 250 fixed offshore platforms installed in both Peninsular Malaysia and East Malaysia (Liu *et al.*, 2016) with 85% of the total numbers being in West Malaysia (Courtesy of Shell and PETRONAS). It is an increase of about 50 numbers of fixed offshore platforms installed in Malaysian water since 2011 (Azman, 2011). These platforms are located on the continental shelf of the South China Sea. These platforms are mainly operated by three main operators, namely Shell Malaysia Exploration and Production (SMEP), Petronas Carigali Sdn. Bhd. (PCSB) and ExxonMobil Exploration & Production Malaysia Inc. SMEP is focusing its operation in West Malaysia and ExxonMobil Exploration & Production Malaysia Inc. operates in Peninsular Malaysia. While being subsidiary of PETRONAS, PCSB is operating in both Peninsular Malaysia and East Malaysia and by default will inherit all these platforms.

Historically, fixed offshore platforms were installed as early as 1960s and the total numbers is growing significantly since then. The distribution of fixed offshore platforms in Malaysia water versus age and year of installation are shown in Figure 1.1 and Figure 1.2:

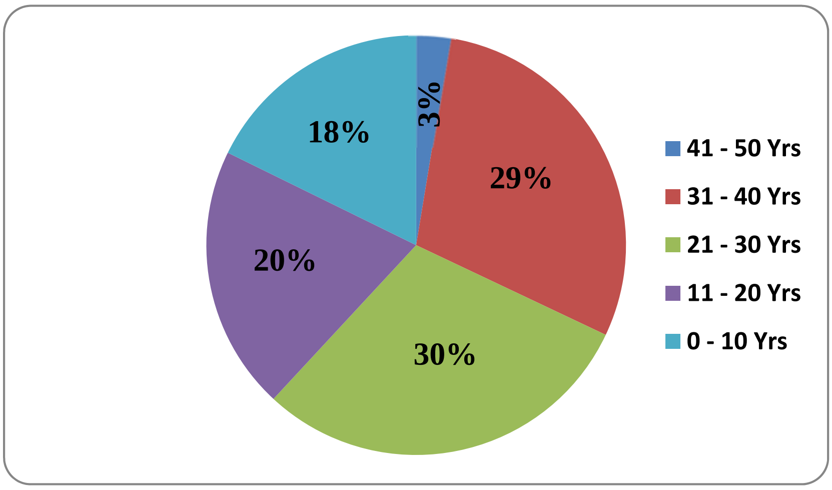

Figure 1.1: Fixed offshore platform in Malaysia versus age (Courtesy of Shell and PETRONAS)

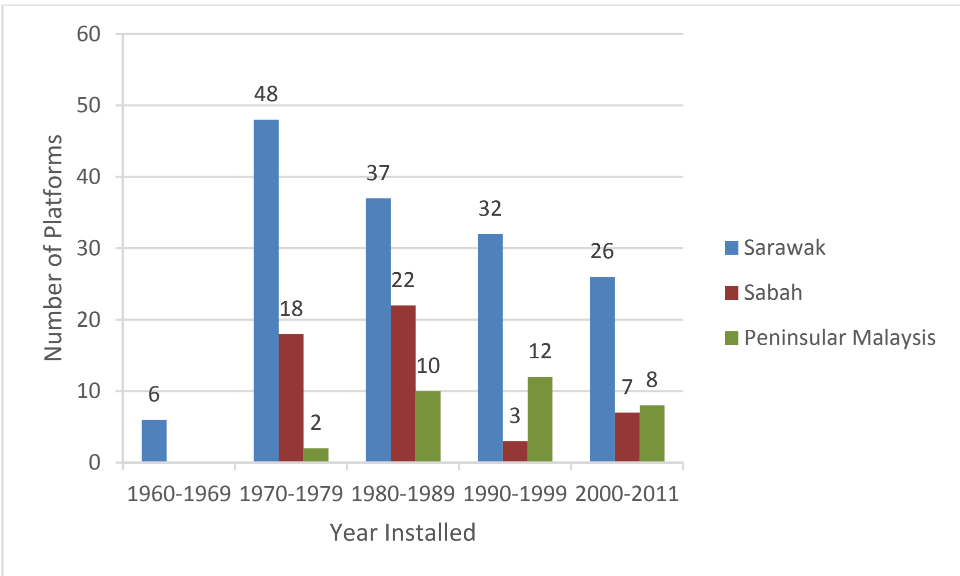

Figure 1.2: Number of fixed offshore platforms in Malaysia water versus installation year (Courtesy of Shell and PETRONAS)

In general, the development of Oil and Gas industry in Malaysia can be summarized in Figure 1.3.

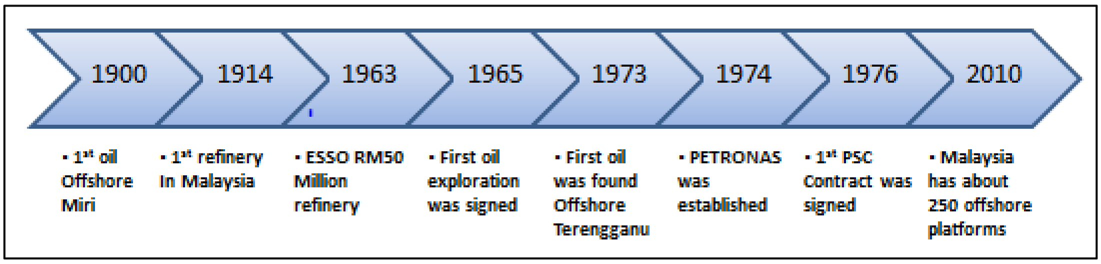

Figure 1.3: Timeline in the development of Malaysia oil and gas industry (Narayanan and Kabir, 2009)

1.1 Research Issue Identification

From Figure 1.1 and 1.2, there are about 250 fixed offshore platforms installed in Malaysian water in 2016. Of these, 32% have exceeded their design life of 30 years while another 30% of platforms have been in operation for more than 20 years and several others are reaching 20 years of age. Therefore, the reliability of offshore platforms has become a very important issue in the Malaysian oil and gas industry as a majority of the jacket platforms in Malaysian are about to exceed their design life (Kurian *et al.*, 2014). Reliability of fixed offshore platform can be assessed through platform probability of failure. Non-linear pushover analysis which is used to calculate the reserve strength ratio (RSR) of existing platforms is crucial because the RSR is to be used in the reliability assessment to calculate the platform probability of failure. RSR describes the level of structural redundancy and resistance of jacket structure to extreme weather condition (Singh *et al.*, 2015). Pushover analysis is widely used in current offshore standards such as American Petroleum Institute (API), International Organization for Standardization (ISO) and Det Norske Veritas (DNV) to evaluate the ultimate capacity of the platform against environmental loading (Golafshani *et al.*, 2011). In short, first, the gravity load is applied followed by the environmental load which is applied incrementally on the jacket structures until a failure mechanism is formed. Figure 1.4 below shows the schematic on how the environmental load is being applied on jacket structure until collapse mechanism is formed.

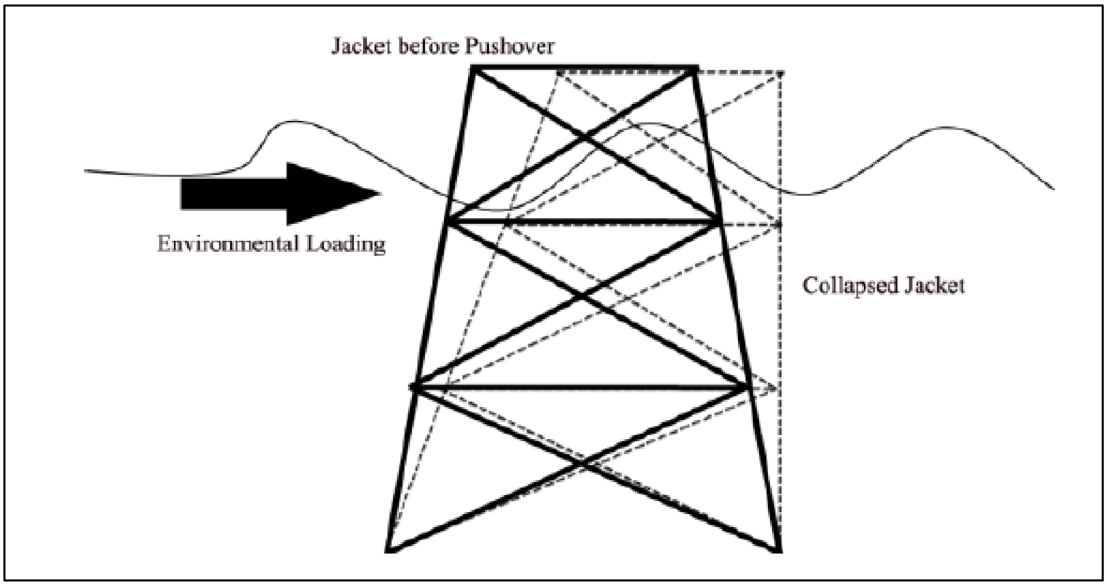

Figure 1.4: Pushover analysis - increasing environmental loading until the structure collapses (Kurian *et al.*, 2014)

The gap identified in the current pushover analysis procedure is the application of the environmental load which does not consider the possibility of wave-in-deck scenario. Thus, the calculated base shear at platforms collapse condition is unrealistic. With the inclusion of wave-in-deck, the actual load on the structure will increase because of the wave reaching the deck and the calculated base shear will be larger than what is modelled in the typical RSR analysis (Singh *et al.*, 2015 & Golafshani *et al.*, 2011). The more accurate and realistic RSR should take into account of wave-in-deck loading contribution toward platform failure. The question on the impact of wave-in-deck to the platform reserve strength ratio will be discussed and answered in this thesis.

Throughout the service life of the offshore platforms, modifications and upgrading activities with the purpose to enhance the efficiency of the system as well as to increase production capacity are becoming continuous activities. These modifications and upgrading activities can be in the form of facilities upgrading/modification, new equipment installation and increase in total number of people on board. All these changes and improvement contribute to increase in platform loading system. Therefore, structural integrity reassessment needs to be carried out to determine their fitness for purposes to accommodate the abovementioned changes. API (2002) and ISO (2007) (e.g. Section 17 and Section 24 respectively) provide general guidelines for the reassessment of existing fixed offshore platforms. In performing the structural integrity reassessment of fixed offshore platforms in Malaysian water several issues are to be investigated and answered such as:

(i) Key parameters that affect the overall structural response of fixed offshore structures in Malaysian water.
(ii) Are fixed offshore platforms in Malaysian water drag or inertia dominant or both drag and inertia dominant structures?
(iii) Methodology to perform structural reliability reassessment for existing platforms at Malaysian water by taking into account wave-in-deck.

1.2 Research Objectives

Due to the business needs to continue production, modification to accommodate additional loadings, damage due to extreme weather and deteriorations due to ageing effect, requalification of existing platforms become necessary and important subject or area to research. The aim of this research is to improve the structural reassessment of existing fixed offshore structures in Malaysian water. To achieve this aim, the following objectives are to be observed:

(i) To quantify the impact of key design parameters which are drag and inertia coefficients, marine growth, current blockage factors and current profile toward structural response of fixed offshore platforms in Malaysian water through sensitivity analysis.
(ii) To propose improved Structural Reliability Assessment (SRA) methodology for fixed offshore structures in Malaysian water by including the effect of wave-in-deck in calculating the platform Reserve Strength Ratio (RSR).

1.3 Significance of the Study

There are several potential benefits and contributions from this research work toward oil and gas industry in Malaysia. The study to quantify the contribution of drag and inertia coefficients toward overall hydrodynamic loading of fixed offshore platform in Malaysian water will provide information whether the fixed offshore platforms in Malaysian water are drag or inertia dominants. The conclusion from this study can be used to justify the significant contribution of marine growth toward overall hydrodynamic loading of the fixed offshore platforms in Malaysian water. Marine growth is known to give adverse effects to the performance of offshore structure through increases the surface roughness of the structure and hence increase the drag coefficient (Jusoh & Wolfram, 1996). Therefore, if the fixed offshore platforms in Malaysian water are drag dominant and sensitive to changes on drag coefficient, then by removing the marine growth will significantly reduce the platforms hydrodynamic loading. With this reduction, the hydrodynamic loading for the fixed offshore platforms as calculated by Morison equation will be significantly reduced. The potential practical application of this finding is to mitigate overstressed members by reducing overall hydrodynamic loading through the removal of the marine growth especially at the splash zone area of the jacket structure instead of performing physical strengthening such as installing a new bracing.

Since the marine growth distribution on structural members vary according to several factors such as geographical location, water depth, water temperature and season, ocean current, platform design and operation (Jusoh & Wolfram, 1996), the international codes and standards are silent in providing guideline on the marine growth distribution to be adopted on the design or reassessment of fixed offshore platforms. Therefore, each locality has its own local design guidelines or requirements on the matter. As for fixed offshore platform at Malaysian water, one of the local design guideline on marine growth distribution is tabulated on Table 2.3. However, the marine growth distribution at water depth (-) 21.0 meter and below is always different from what been reported from the actual marine growth measurement during underwater inspection. This research will study the contribution of marine growth at elevation below (-) 21.0 meter toward the overall global loading of the platforms and to determine if the existing platforms in the Malaysian water that were designed based on this guideline were under designed or otherwise. Furthermore, the practical application from the outcome of this study will be providing recommendation if the local design guidelines require any update.

Another primary objective and also the strength of this research is to propose improvement to close that identified gap in structural reliability assessment of fixed offshore platform in Malaysia water. The identified gap in performing structural reliability assessment of fixed offshore platforms in Malaysian water is that the nonlinear pushover analysis is performed through progressive increment of the environmental load until structure collapse without considering the increment in wave height (Singh *et al.*, 2015). For example, the wave-in-deck that potentially occurs is not considered in the analysis. This approach is considered unrealistic and underestimating the platform collapse load because the contribution of wave-in-deck can be very significant. Therefore, the proposed structural reliability assessment provides improvement by considering the contribution of wave-in-deck in the calculation of platform reserve strength ratio and also to provide formulation to determine the wave height that causes platform collapse. This allows the effect of wave-in-deck which significantly increases the total base shear load of the platform structures to be accounted in the calculation of platform RSR and the calculated RSR is become more realistic and accurate.

1.4 Scope of Research

In this research, four (4) existing fixed offshore platforms in Malaysian water are used as the samples/subjects in the study of the effect of marine growth profile, drag coefficient, inertia coefficient, current blockage factor and current profile toward fixed offshore platforms response. In the study on the application of the proposed Structural Reliability Assessment (SRA) methodology, two (2) existing platforms in Malaysian water are used as samples. These platforms are located in different regions in Malaysian water such as Sarawak water and Sabah water where most of fixed offshore platforms were installed. Furthermore, the platforms are also selected based on platform configuration and water depth.

The research objective is achieved through literature and information search, conducting case study and sensitivity study and performing structural integrity assessment by using proposed SRA methodology. The literature and information search are carried out to gather information on the requalification of existing platforms, design of fixed offshore platforms, key design parameters that affecting the magnitude of environmental loading on the fixed offshore platforms and ultimate strength analysis of fixed offshore platforms. Through the literature and information search, the latest development and area of improvement are identified. The literature review includes technical reports, published and conference papers, previous research document, international standards or guidelines and text books.

This thesis covers several types of studies such as case study and sensitivity study. For the case study, structural integrity reassessment of fixed offshore platform which covers stress check, foundation check, joint check and deflection allowable check has been performed. For the sensitivity study, the effect of platform design parameters such as drag and inertia coefficients, marine growth distribution and current blockage factors toward global response of the fixed offshore structures will be investigated. Furthermore, sensitivity study on the Alpha parameter is also conducted to investigate the influence of fixed offshore platforms configuration. The results and outcomes of the case study and sensitivity study are discussed in Chapter 4 and Chapter 6.

Structural Reliability Assessment (SRA) methodology for fixed offshore structures in Malaysian water has been proposed by including the effect of wave-in-deck in calculating the platform RSR The wave-in-deck load is calculated based on simplified silhouette method as per ISO (2007), Section A.24.7.3. The ultimate strength assessment based on proposed SRA methodology and the calculation of the Reserve Strength Ratio (RSR) of the platform have been carried out. The governing failure mode of the structure is also discussed. The platform probability of failure based on the proposed SRA methodology is then calculated and compared against existing method such as Simplified Structural Reliability Assessment (SSRA).

REFERENCES

Allender, J. H. and Petrauskas, C. (1987). Measured and Predicted Wave Plus Current Loading on a Laboratory Scale, Space Frame Structure. *Offshore Technology Conference*. 27-30 April. Houston, Texas.

Al-Yacouby, A. M., Kurian, V. J., Sebastian A. A., Liew, M. S., Idichandy, V .G. (2014). Effects of Marine Growth on Hydrodynamic Coefficients of Rigid Tubular Cylinders. *Applied Mechanic and Materials*. Volume 567, 247-252.

American Petroleum Institute, API (1993). *Recommended Practice for Planning, Designing, and Constructing Fixed Offshore Platforms – Load and Resistance Factor Design*. Washington DC: American Petroleum Institute.

American Petroleum Institute, API (2002). *Recommended Practice for Planning, Designing, and Constructing Fixed Offshore Platforms – Working Stress Design*. Washington DC: American Petroleum Institute.

American Petroleum Institute, API (2004). *Bulletin 2U-Bulletin on Stability Design of Cylindrical Shells*. Washington DC: American Petroleum Institute.

Ayob, M. S., Mukherjee, K., Kajuputra, A. E., Wong, B. S. and Salleh, F. M. (2014). Requalification of Offshore Jacket Structures in Malaysian Waters. *Offshore Technology Conference Asia*. 25-28 March. Kuala Lumpur, Malaysia.

Azman, M. F. N. (2011). *Sensitivity Study of Environmental Load to Reliability Index for Malaysian Region*. M. Sc. Thesis, Universiti Teknologi Petronas, Malaysia.

Barltrop, N. D. P. and Adam, A. J. (1991). *Dynamics of Fixed Marine Structure*. (3rd ed.). London: Butterworth Heinemann Ltd.

Bea, R. G. (1990). Reliability Criteria for New and Existing Platforms. *Offshore Technology Conference*. 7-10 May. Huston, Texas, USA.

Bea, R. G. and Craig, M. J. K. (1993). Developments in the Assessment and Requalification of Offshore Platforms. *Offshore Technology Conference*. 3-6 May. Huston, Texas, USA.

Brown, A. (2004). *Sarawak Waters Joint Metocean Design Criteria*. MRD 5.1. (Confidential Report)

Chakrabarti, S. K. (1981). Hydrodynamic Coefficients for a Vertical Tube in an Array. *Applied Ocean Research*. Volume 3(1), 2-12.

Chakrabarti, S. K. (1982). Wave Force Coefficients for Rough Vertical Cylinder. *Journal of Waterway. Port, Coastal and Ocean Engineering.* Volume 110(1), 101-104.

Chakrabarti, S. K. (1987). *Hydrodynamic of Offshore Structures*. Southampton, UK: WIT Press.

Chakrabarti, S. K. (Ed.) (2005). *Handbook of Offshore Engineering*. San Francisco: Elsevier.

Chella, M. A. (2016). *Breaking Wave Characteristics and Breaking Wave Force on Slenders Cylinder*. PhD Thesis. Norwegian University of Science and Technology.

Copello, S., Magliano, M. and Manera, A. (2017). Minimum Requirements for Decision Making and Maintenance of Existing Fixed Offshore Structures. *13th Offshore Mediterranean Conference and Exhibition*. 29-31 March. Ravenna, Italy.

Dean R. G. and Dalrymple, R. A. (1991). *Water Wave Mechanics for Engineers and Scientists*. New Jersey, USA: World Scientific.

Det Norske Veritas (2010). *Environmental Condition and Environmental Load: DNV-RP-C205*. Hovik, Norway: Det Norske Veritas.

Efthymiou, M. and van de Graaf, J. W. (1997). *Reliability Based Design and Re-assessment of Fixed Steel Platforms: SIEP 97-5050*. Unpublished, Shell. (Confidential Document).

Efthymiou, M. and van de Graaf, J. W. (2011). Reliability and (Re)Assessment of Fixed Offshore Steel Structures. *Proceeding of the ASME 2011 30th International Conference on Ocean, Offshore and Arctic Engineering*. 19-24 June. Rotterdam, Netherland.

Engineering Dynamics Incorporated (2001). *User's Manual: Introduction to SACS Programs*. (5th ed.). Engineering Dynamics Incorporated.

Ersdal, G. (2005). *Assessment of Existing Offshore Structures for Life Extension*. PhD Thesis. University of Stavanger.

Etterdal, B., Scherf, I. and Grigoran, H. (2001). Strengthening of Ekofisk Platforms to Ensure Continued and Safe Operation. *Offshore Technology Conference*. 30 April – 3 May. Houston, Texas, USA.

Golafshani, A. A., Hossein, E., Vahid, B. and Tore, H. (2011). Assessment of Offshore Platforms under Extreme Waves by Probabilistic Incremental Wave Analysis. *Journal of Constructional Steel Research*. Volume 67. 759-769. Elsevier.

Grigorian, H., Scherf, I. and Yu, W. C. (2001). Cost-Efficient Structural Upgrade and Life Extension of Ekofisk Platforms with Use of Modern Reassessment Techniques. *Offshore Technology Conference*. 30 April - 3 May 2001. Huston, Texas.

Hallam, M. G., Heaf, N. J. and Wootton, L. R. (1978). Dynamic of Marine Structures – Method of Calculating the Dynamic Response of Fixed Structure Subject to Wave and Current Action: Report UR 8. (2nd ed.). London: Construction Industry Research and Information Association. Underwater Engineering Group, CIRIA.

Haritos, N. (2007). Introduction to the Analysis and Design of Offshore Structures – An Overview. *Electronic Journal of Structural*. Volume 7, 55-65.

Grigorian, H., Scherf. I., Yu, W. C. and Christensen, O. (2001). Cost-Efficient Structural Upgrade and Life Extension of Ekofisk Platforms with Use of Modern Reassessment Techniques. *Offshore Technology Conference*. 30 April – 3 May. Huston, Texas, USA.

Gronbech, J., Sterndorff, M. J. and Grigorian, H. (2001). Hydrodynamic Modelling of Wave-in-Deck Forces on Offshore Platform Decks. *Offshore Technology Conference*. 30 April – 3 May. Houston, Texas, USA.

Hendriks, P. (2009). Assessment of Dynamic Amplification of Fixed Offshore Structure due to Wave Loading: ECSM-CS-8380. Unpublished, Shell. (Confidential Report).

Henry, Z. (2017). Structural Integrity Analysis of Fixed Offshore Jacket Structures. *Article in Press Universiti Teknologi Malaysia*. Volume 40.

Hines, I. M. (1987). *Practice for the Dynamic Analysis of Fixed Offshore Platforms for Extreme Storm Conditions: EP 87-0170*. Unpublished, Shell. (Confidential Report).

Hsu, T. H. (1984). *Applied Offshore Structural Engineering: Practical Design Methods, Formulas and Data*. Houston, Texas, USA: Gulf Publishing Company.

Idrus, A., Potty, N. and Nizamani (2011). Tubular Strength Comparison of Offshore Jacket Structures Under RP2A and ISO 19902. Journal – The Institution of Engineers Malaysia. Volume 72 (3), 41-40.

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

Jusoh, I. and Wolfram, J. (1996). Effect of Marine Growth and Hydrodynamic Loading on Offshore Structures. Jurnal Mekanikal. Volume 1, 77-98.

Kanter, P. A., Scherf, I., Petterson, B., Osnes, J., Grigorian, H., Yu, W. C. and Christensen, O. (2001). Instrumentation of Ekofisk Platforms. *Offshore Technology Conference*. 30 April – 3 May. Houston, Texas, USA.

Keulegan, G. H., Carpenter, L. H. (1958). Forces on cylinders and plate in an oscillating fluid. *Journal of Research of the National Bureau of Standards*. Volume 60(5), 423.

Knight, R. M. and Daniel, J. J. S (1993). World Trends in Major Offshore Structures: 1970 – 1999. *Proceedings of Offshore 1993 IMARE/RINA, Joints Offshore Group 3rd International Conference*. 17-18 February. London, United Kingdom.

Kurian, V. J., Voon, M. C., Wahab, M. M. A. and Liew, M. S. (2014). System Reliability Assessment of Existing Jacket Platform in Malaysian Waters. *Research Journal of Applied Sciences, Engineering and Technology*. Volume 8 (23). 2305-2314.

Le Mehaute, B. (1969). *An Introduction to Hydrodynamics and Water Waves*. Miami, Florida, USA: Pacific Oceanographic Labs.

Liew, M. S., Lim, E. S. and Tengku Shahdan, T. N. (2012). Spectral Analyses of Sea-State Wave Data for the Development of Offshore Metocean Applications: A Malaysian Case Study. Recent Advances in Engineering. 246-253.

Liu, Y., Sun, C., Sun, J., Li, H., Zhan, W., Yang, Y. and Zhang, S. Y. (2016). Satellite Data Lift the Veil on Offshore Platforms in South China Sea. *Scientific Report*.

Manzocchi, M. and Atia, M. (2015). Development of Reliability-Based Assessment Criteria Against Extreme Environments For Steel Fixed Offshore Structures With Significant Permanent Loading. International Petroleum Exhibition and Conference. 9-12 November. Abu Dhabi, UAE.

Marley, M., Etterdal, B. and Grigorian, H. (2001). Structural Reliability Assessment of Ekofisk Jacket Under Extreme Loading. *Offshore Technology Conference*. 30 April - 3 May 2001. Houston, Texas.

Morison, J. R., O'Brien, M. P., Johnson, J. W. and Schaaf, S. A. (1950a). The Force Exerted by Surface Waves on Piles. *Petroleum Transactions*, AIME. Volume 189. 149-154.

Morison, J. R., Johnson J. W. and O'Brien, M.P. (1950b). Experimental Studies of Forces on Piles. Journal of Petroleum Technology. Volume 2(05), 340-370.

Moses, F. and Stahl, B. (2000). Calibration Issues in Development of ISO Standards for Fixed Steel Offshore Structures. *Journal of Offshore Mechanics and Arctic Engineering*. Volume 122. 52-56.

Narayanan, S, P. and Kabir, M. B. M. A. (2009). Structural Integrity Management for Fixed Offshore Platforms in Malaysia. *World Academy of Science, Engineering and Technology*. Volume 58. 1079-1087.

Nezamian, A. and Altmann, J. (2013). An Oil Field Structural Integrity Assessment for Re-Qualification and Life Extension. Proceedings of the ASME 2013 32nd International Conference on Ocean, Offshore and Arctic Engineering, OMAE. 9-14 June. Nantes, France.

Okada, H. and Murotsu, Y. (1990). A Method for Reliability Assessment of Aged Jacket Structures Based on Ultimate Strength Analysis. *Proceedings of the First Pacific/Asia Offshore Mechanics Symposium*. 24-28 June, Seoul Korea.

Rienecker, M. and Fenton, J. (1981). A Fourier Approximation Method for Steady Water Waves. *Journal of Fluid Mechanics*. Volume 104. 119-137.

Rizal, A. (2011). Global Ultimate Strength Analysis for SBO platform: SMJT-E - Report ID: RD-PLE-CSP-RBI-S309. Unpublished, Group Technical Solution (GTS). (Confidential Report).

Sagrilo, L. V. S., Lima, E. C. P. and Rodriguez (1996). Reassessment of Fixed Offshore Structures Using Reliability and Nonlinear Analyses. *Proceeding of the Sixth (1996) – International Offshore and Polar Engineering Conference*. 26-31 May. Los Angeles, USA.

Sarpkaya, T. (1976). In-line and Transverse Forces on Cylinders in Oscillatory Flow at High Reynolds Number. *Proceeding of. 8th Annual Offshore Technology Conference*. 3-6 May. Huston, Texas, USA, 95-108.

Sarpkaya, T. (1979). Hydrodynamic forces on various multiple-tube riser configurations. *Offshore Technology Conference*. 30 April-3 May. Huston, Texas, USA.

Singh, D., Panneerselvam, N. and Kumar, D. (2015). Reliability Analysis of Strength of Offshore Jacket in Indian Western Offshore. *Proceeding of Society of Petroleum Engineers Conference*. 24-26 November. Mumbai, India.

Sorkhabi, R. (2010). Miri 1910: The Centenary of oil Discovery in Sarawak. *Geoexpro*, Volume 7/2, page 44-49.

Standard Engineering Specification (2005). *SES 10.1 Revision 4 - Design of Fixed Offshore Structures*. Unpublished, Shell. (Confidential Report).

Standard Engineering Specification (2015). *SES 10.1 Revision 6 - Design of Fixed Offshore Structures*. Unpublished, Shell. (Confidential Report).

Stewart, G., Efthymiou, M., and Vugts, J. H. (1988). Ultimate Strength and Integrity Assessment of Fixed Offshore Platforms. *Proceedings of the 5th International Conference on the Behaviour of Offshore Structure*. June. Trondheim, Norway, 1205-1221.

Taylor, P. H. (1991). Current Blockage: Reduced Forces on Offshore Spare-Frame Structures. *Offshore Technology Conference*. May 6-9. Houston, Texas, USA.

The Commission for Energy Regulation (2013). *CER/13/073*. Dublin: The Commission for Energy Regulation.

United Kingdom Department of Energy (1989). *Fluid Loading on Fixed Offshore Structures - OTH 90 322*. London, W.S. Atkins Engineering Sciences, HMSO Books.

Van de Graaf, J. W. and Tromans, P. S. (1992). A Substantiated Risk Assessment of a Jacket Structure. *Offshore Technology Conference*. 4-7 May. Houston, Texas, USA.

Zhang, Y. and Jin, W. (2011). Reliability Evaluating of a Jacket Platform Example. *Proceeding of the Twentieth (2010) International Offshore and Polar Engineering Conference*. 20-25 June. Beijing, China.