EFFECT OF SCOURING ON PILE PERFORMANCE OF FIXED OFFSHORE JACKET STRUCTURES IN MALAYSIA

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DEDICATION

I dedicate my work to my family, spouse, and close acquaintances.

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اِلَهِى اَنْتَ مَقْصُوْدِيْ وَرِضَاكَ مَطْلُوْبِيْ

"In the name of Allah, the most gracious, the most compassionate and also to our prophet Muhammad s.a.w of Allah peace is upon him"

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ABSTRACT

A large number of facilities and offshore infrastructures have exceeded their original design life. The options are either decommissioning the facilities or extending the design life to the desired timeline without compromising the safety and integrity aspects of the facilities. The aspect of ageing management is the most important factor in order to control and mitigate the degradation of facilities. Scour in general is defined as erosion of loose seabed material directly around offshore structures. It is part of the component to be considered in the life extension of the offshore facilities. Code and standard practices have suggested various recommendations for the scour depth to be adopted during the initial design stage. Over estimation on the scour depth has an impact on the pile factor of safety, pilehead displacement and pile unity check which relates to the economic perspective. Therefore, it is crucial to determine the scour depth in the design stage. This study investigated the significant impact of scour depth on the pile performance, analysed the pile performance based on the design scour against the actual scour, and established the correlation between scour effect and pile performance. Fixed offshore platforms were selected from three different regions: Peninsular Malaysia Operation (PMO), Sarawak Operation (SKO), and Sabah Operation (SBO) for this study. Structural Analysis Computer System (SACS) was employed to model the structural member of the platform and the pile foundation. Static in-place analysis with pile soil interaction was conducted for the two scour case studies (actual and designed values). Results were scrutinised to establish the relation between scour depth and pile performance. The results showed pile unity check is lower than design unity check by a maximum difference of -7.6%. Minimum pile factor safety for actual scour was increased from the design with a maximum difference of 0.31%. A difference of -27.75% between actual and design value was recorded for maximum pilehead displacement. The scour depth increased, directly proportional to the pile unity check and pilehead displacement, whereas pile factor of safety was the other way around. Scour had a significant impact on the lateral load-capacity and stiffness of the pile, led to the increase in the magnitude of bending moments along the pile shaft. The findings are significant to assist the industry, especially operators to reach the optimal design scour depth.

ABSTRAK

Sebilangan besar kemudahan dan infrastruktur luar pesisir telah melebihi hayat rekabentuk asal. Pilihan adalah samada penyahtauliahan kemudahan atau melanjutkan hayat rekabentuk kepada jangka masa yang dikehendaki tanpa menjejaskan aspek keselamatan dan integriti fasiliti. Aspek pengurusan penuaan adalah faktor paling penting untuk mengawal dan mengurangkan kemerosotan fasiliti. Kerukan secara umum ditakrifkan sebagai hakisan bahan dasar laut yang longgar secara langsung di sekitar struktur luar pesisir. Ia adalah sebahagian daripada komponen yang harus dipertimbangkan dalam melanjutkan hayat kemudahan luar pesisir. Kod dan amalan piawai telah mencadangkan pelbagai cadangan kepada kedalaman kerukan untuk diguna pakai semasa peringkat permulaan rekabentuk. Lebihan anggaran pada kedalaman kerukan memberi kesan kepada pemeriksaan kesatuan cerucuk, faktor keselamatan cerucuk dan anjakan cerucuk yang berkaitan dengan perspektif ekonomi. Oleh itu, sangat penting untuk menentukan kedalaman kerukan dalam peringkat rekabentuk. Kajian ini meneliti kesan ketara kedalaman kerukan keatas prestasi cerucuk, menganalisis prestasi cerucuk berdasarkan rekabentuk kerukan terhadap kerukan sebenar dan mewujudkan hubungan antara kesan kerukan dan prestasi cerucuk. Pelantar luar pesisir telah dipilih dari tiga wilayah berbeza: Operasi Semenanjung Malaysia (PMO), Operasi Sarawak (SKO) dan Operasi Sabah (SBO) bagi kajian ini. Sistem Komputer Analisis Struktur (SACS) digunakan untuk permodelan anggota struktur pelantar dan asas cerucuk. Analisis *"Static In-place"* dengan interaksi tanah cerucuk dijalankan untuk dua kajian kes kerukan (nilai sebenar dan rekabentuk). Keputusan telah diteliti untuk mewujudkan hubungan antara kedalaman kerukan dan prestasi cerucuk. Keputusan ini menunjukkan pemeriksaan kesatuan cerucuk lebih rendah berbanding pemeriksaan kesatuan rekabentuk dengan perbezaan maksimum -7.6%. Faktor keselamatan cerucuk minimum untuk nilai sebenar meningkat daripada rekabentuk dengan perbezaan maksimum 0.31%. Perbezaan sebanyak -27.75% antara nilai sebenar dan rekabentuk dicatatkan untuk anjakan cerucuk maksimum. Peningkatan kedalaman kerukan, berkadar langsung dengan pemeriksaan kesatuan cerucuk dan anjakan cerucuk, manakala faktor keselamatan cerucuk adalah sebaliknya. Kerukan mempunyai impak yang ketara terhadap kapasiti beban sisi dan kekukuhan cerucuk yang membawa kepada peningkatan magnitud momen lenturan di sepanjang cerucuk. Hasil kajian ini signifikan untuk membantu industri, terutamanya pengendali struktur luar pesisir bagi mencapai kedalaman kerukan rekabentuk yang optimum.

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LIST OF ABBREVIATIONS

AFC	-	Approve for Construction
AISC	-	American Institute Steel Construction
API	-	American Petroleum Institute
BS	-	Base Shear
FOS	-	Factor of Safety
OM	-	Overturning Moment
PMO	-	Peninsular Malaysia Operation
PSI	-	Pile Soil Interaction
SACS	-	Structural Analysis Computer Software
SBO	-	Sabah Operation
SKO	-	Sarawak Operation
UC	-	Unity Check
ULS	-	Ultimate Limit State

LIST OF SYMBOLS

C_d	-	Drag coefficient
C_m	-	Inertia coefficient
D, d	-	Diameter
δ	-	Displacement
Δ_{uc}	-	Percentage difference between actual and design unity check
Δ_{fos}	-	Percentage difference between actual and design factor of safety
Δ_{disp}	-	Percentage difference between actual and design displacement
F	-	Force
Fb	-	Allowable bending stress
F_d	-	Drag component
F_i	-	Inertia component
Fbx	-	Bending stress in x direction
fby	-	Bending stress in y direction
Fxc	-	Critical local buckling stress
I	-	Moment of Inertia
p	-	Pressure
π	-	Mathematical constant approximately equal to 3.1416
v	-	Velocity
ρ	-	Fluid density
P-Y	-	Lateral soil resistance deflection
Q-Z	-	Relation between mobilized end bearing resistance and axial tip deflection
r	-	Radius
Re	-	Reynold Number
T-Z	-	Relation between mobilized soil-pile shear transferred and local pile deflection
u	-	Water particle velocity
$\dot{u}$	-	Water particle acceleration

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CHAPTER 1

INTRODUCTION

1.1 Oil and Gas Overview in Malaysia

Malaysia has tremendous potential to meet the rising demand for energy consumption by itself. They had begun collecting and processing oil and natural gas effectively from the beginning of the last century. Overall primary energy supply has been growing since the last 18 years. In 2008, it was about 64 Mtoe, representing a rise of more than 200 % from 1990 (Ong HC, 2011).

Since the first oil well was drilled in Miri, Sarawak, in 1910, oil and gas production has been a mainstay of Malaysia's growth. The first oil discovered by Shell (known as The Grand Old Lady) began with a production rate of 83 barrels per day (bbls/d) and reached a peak of 15,000 bbls/d in 1929. Until the 1950s, there were no other drilling operations in Borneo or Peninsular Malaya. Petroleum activity increased dramatically in the 1960s as a result of the discovery and development of offshore fields in Borneo. Offshore oil exploration on Peninsular Malaysia's east coast began in the late 1960s. In the 1970s, some Malaysian oil fields produced 90,000 to 99,000 barrels per day (Bank Pembangunan, 2011).

Initially, foreign oil companies dominated Malaysia's oil and gas industry, with Shell and Esso being the two major players. This was followed by a number of other foreign corporations, including Conoco, Mobil, and Aquitaine. PETRONAS, the national company, first appeared on the scene in 1974 (Bank Pembangunan, 2011). Since then, oil and gas exploration and production have been carried out under a Production Sharing Contract (PSC), under which PETRONAS granted exploration rights to local and international companies. Each contract requires the PSC Contractor to provide all financing and bear all risks associated with exploration, development, and production activities in exchange for a percentage of total production. (Razali, 2005).

Presently, more than 70 PSCs with various companies, including its Exploration and Production (E and P) subsidiary PETRONAS Carigali Sdn. Bhd., which accounts for 43 % of total Malaysian production. Shell had a 22 % share of total production, and ExxonMobil had a 16 % share (Bank Pembangunan, 2011). In the year 2000, Peninsular Malaysia Operation (PMO), Sarawak Operation (SKO) and Sabah Operation (SBO) operated over 300 offshore platforms in Malaysia (Wan Abdullah Zawawi, 2012). According to Ayob *et al.* (2014), 65 % of 191 offshore platforms completed their design life in 2014 and the figure would grow to 78 % in 2019.

The types of offshore platforms differ from structure system point of view, which developed over time from the requirement to obtain the oil and gas in locations with greater water depth. The offshore platforms are usually divided into two, fixed platforms and floating platforms (Chakrabarti, 2005; El-Reedy, 2012). Fixed platforms are supported either by a pile-based jacket type or the gravity-based type. Whereas for floating platforms, production, storage, and offloading (FPS) can be tension leg platform, spar, semi-submersible and floating.

The type of offshore platform usually depends on the water depth and mode of operation of the proposed location (Reddy and Swamidas, 2014). Figure 1.1 shows the different types of offshore platform. Building a fixed style platform may be feasible and economical for the shallow water level up to 500 m. In terms of viability and economics, floating platform has always been a better choice for deep water levels (Sadeghi, 2007; Nouban *et al.*, 2016).

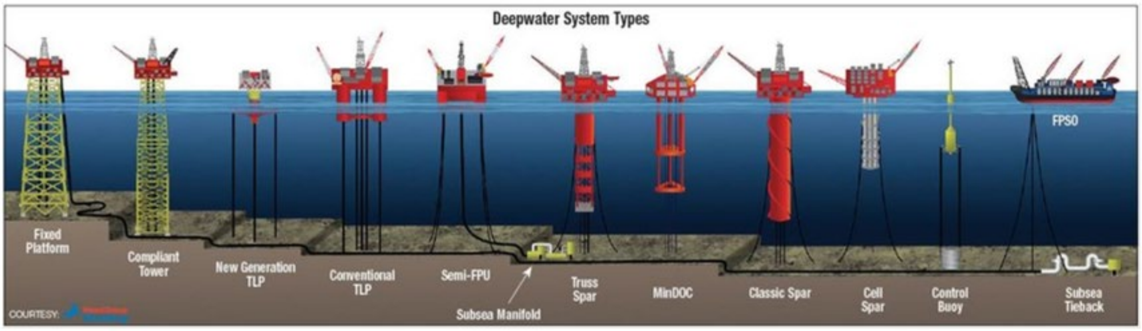
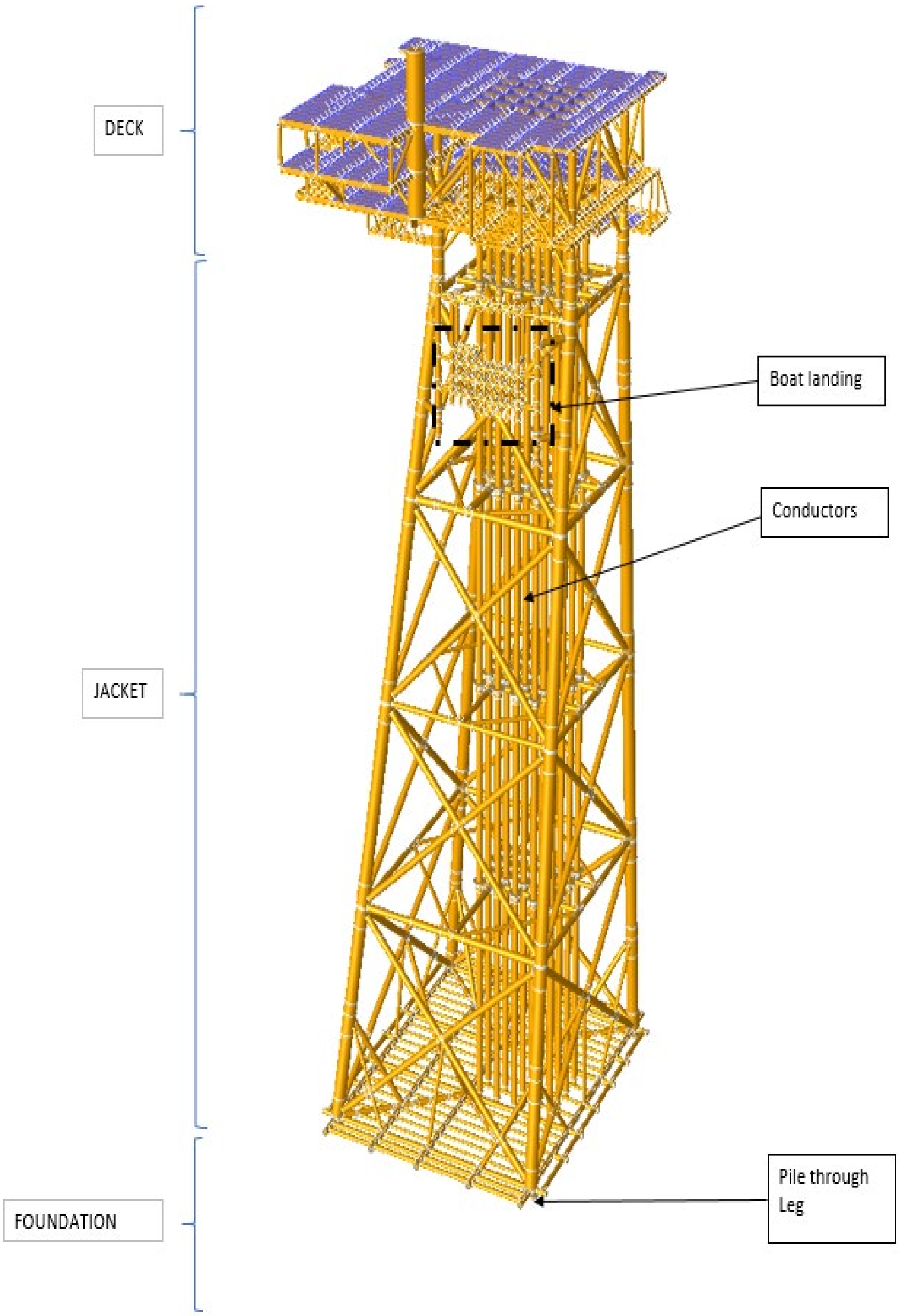
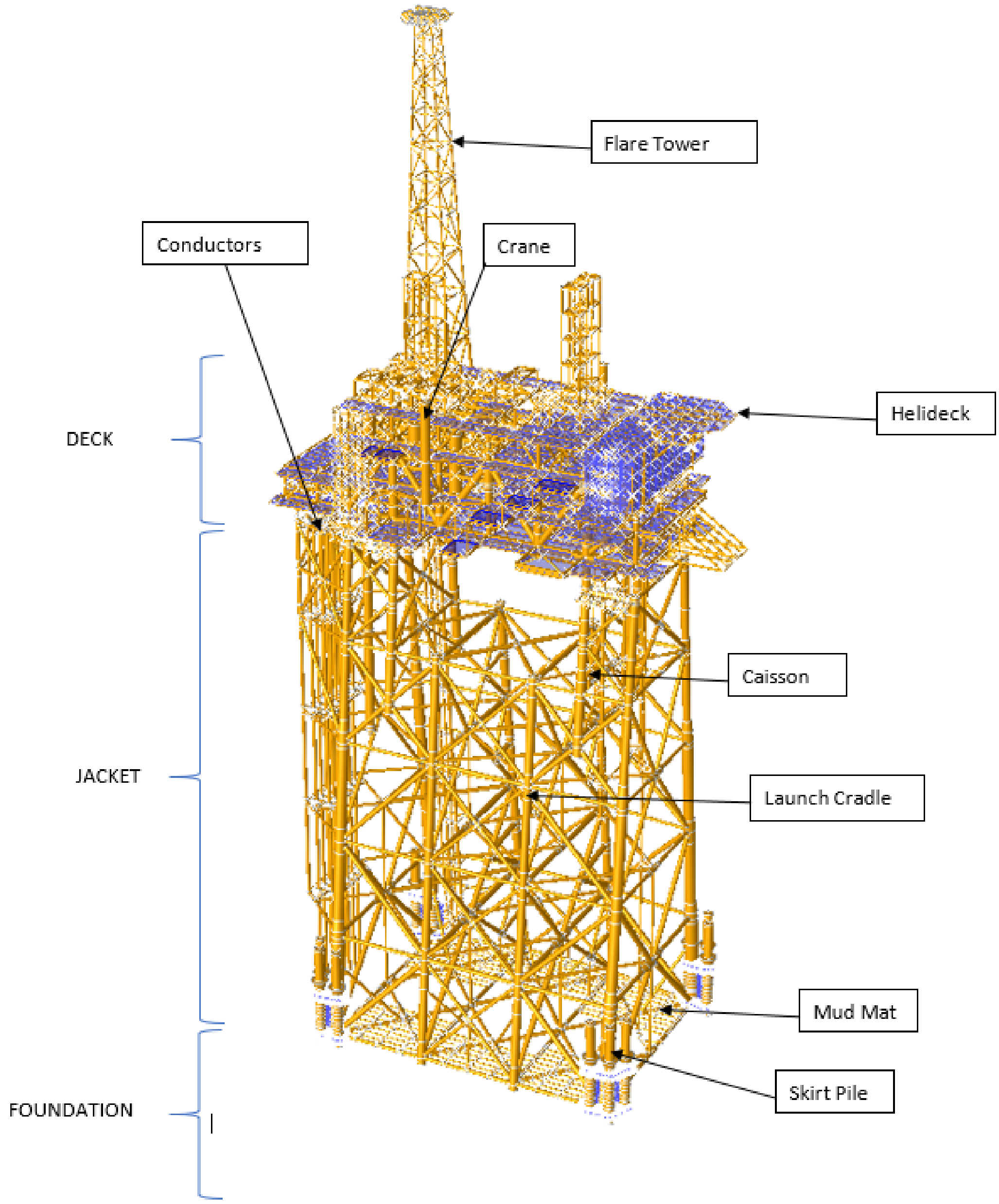


Figure 1.1 Deepwater system types
(Source: (Nguyen, 2015))

Most of the existing offshore platforms in Malaysia are a fixed template jacket installed in water with a depth less than 150 m. The platforms, such as central processing platform, drilling platform, compression platform, and living quarters platform, are defined by its function (Chakrabarti, 2005; Sadeghi and Bichi, 2018). The main components of a typical fixed template jacket consist of a topside, jacket and pile foundation while other components are considered as an appurtenance. Figure 1.2 shows the typical fixed jacket template for wellhead and process platform.



(a) Typical wellhead platform



(b) Typical central processing platform

Figure 1.2 Typical view offshore platform modelled in Structural Analysis Computer Software (SACS)

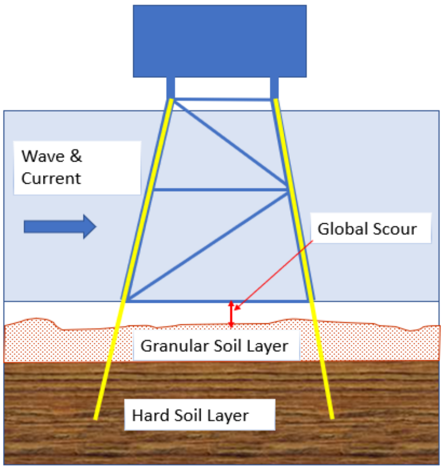
1.2 Challenges in Ageing Offshore Structures

In the year 2020, Malaysia had roughly 378 shallow water fixed platforms operated by 30 PSC contractor in the three regions: namely SKO, SBO, and PMO (PETRONAS, 2020). As stated in 2008, 48 % of the platforms have gone beyond their 25 years design life. SKO contributed 28 % , 12 % of SBO and 8 % of Peninsular Malaysia (Shuhud, 2008). Therefore, the number of ageing platform is increasing with time.

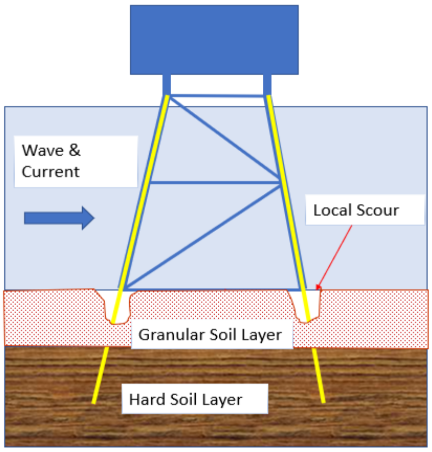
Lifetime extension is defined as the increase in life of the facility without increasing the facility risk (Palkar, 2012; Li *et al.*, 2021). Life extension due to additional and/or enhance oil and gas recoveries has its own challenges, mostly due to the structural integrity (Nicholas *et al.*, 2006; Seyyedattar *et al.*, 2020; Tarpø, 2020). Material degradation, obsolescence and organisational issues are the three main aspects of the management of ageing offshore facilities. The erosion process of loose seabed material around offshore structure is known as a scour and it is part of the material degradation (Palkar, 2012; Ma *et al.*, 2018). Changes from the original design assumption such as scour depth is one of the criteria for assessing platform life extension (ISO, 2007; Schendel, 2018).

The removal of seafloor soils caused by waves and currents is known as scour. Such erosion can be caused by a natural geological process or by structural elements interfering with the natural flow regime near the seabed (American Petroleum Institute, 2007; Welzel *et al.*, 2018). There are two types of scours which are common to occur according to El-Reedy (2012). Global scour affects the areas of the piles, usually twice the area covered by the platform local scour occurs around specific areas of the structure such as piles. Figure 1.3 shows the two different types of scours that generally occur.

Bijaker (1980) identifies three mechanisms that contribute to scour. To begin, the presence of the object causes an increase in water velocity around the object, a vortex trail shed on the downstream side of the object, and a vertical component of seawater velocity.



(a) Global scour



(b) Local scour

Figure 1.3 General types of scours

Sand or silt soils at water depths below approximately 130 feet (40 meters) are especially vulnerable to scouring, but scouring has been found in cobbles, gravel and clays; the intensity of scouring in deeper water depends on the vigorousness of currents and waves (Welzel *et al.*, 2018). Scouring can lead to the removal of vertical and lateral foundation support, causing undesirable mat foundation settlements, and overpowering of foundation components (Akhlaghi *et al.*, 2020). Scour should be accounted for in design and/or considered for its mitigation (American Petroleum Institute, 2007; Menzel and Paschen, 2017). Scour can increase the length of exposure of the structure subjected to the additional hydrodynamic loading (Palkar, 2012; Bayton and Black, 2019).

Figure 1.4 shows the sample of local scour that occurred below the mud mat structural framing. The scour was recorded during an underwater inspection campaign in 2018, five years after the platform was installed. As stated, the scour depth recorded was 292 mm, while during the design stage, the scour adopted was 1372 mm. This shows that the scour adopted during design stage was overestimated and led to the over design of structure's member. Further description on the fundamental of scour and its significance in the design of offshore structure will be explained in *Chapter 2*.

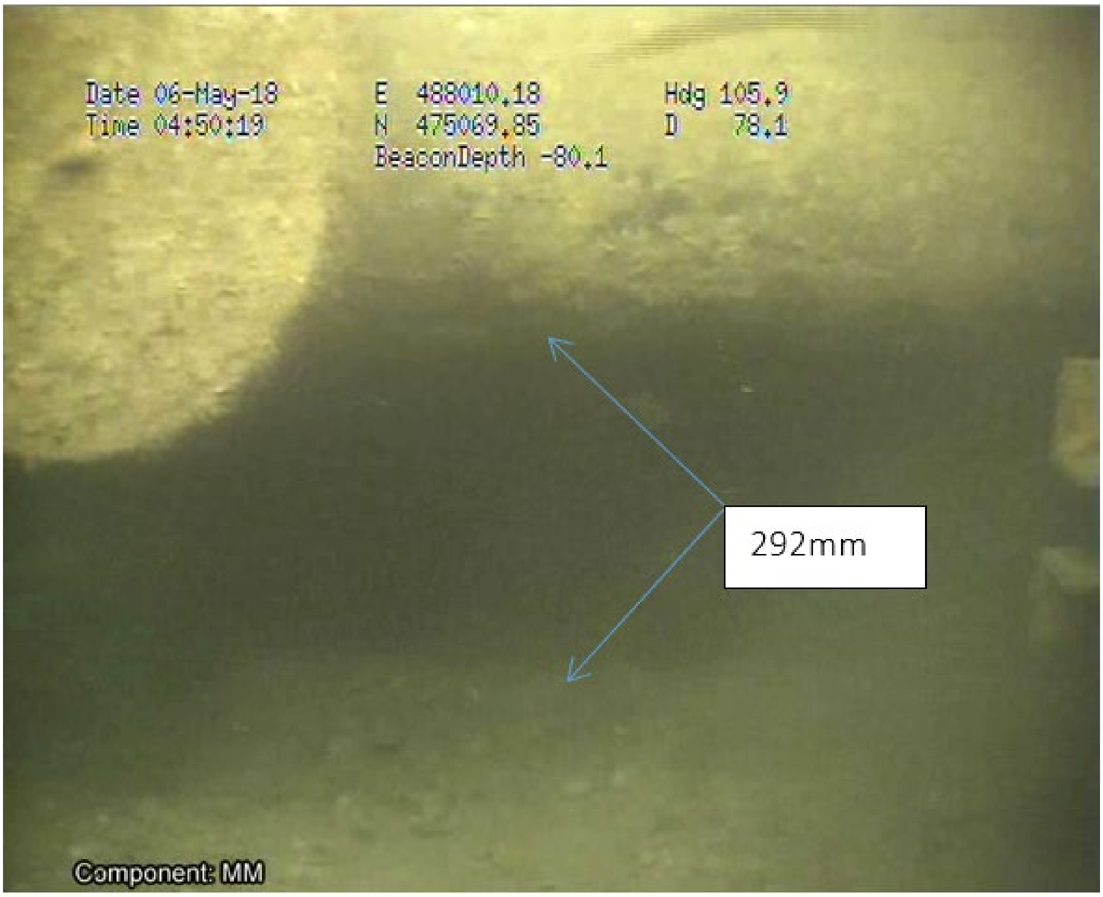


Figure 1.4 Side view of local scour near leg below the mud-mat framing (Source: (International Petroleum Corp, 2018))

1.3 Problem Statement

Scour is a natural occurrence that can cause additional forces to be exerted on the offshore structure. Scour has become a serious concern since strong bottom current with long durations have been observed in many deep water developments (Niedoroda *et al.*, 2003b). Removing the seabed sediments surrounding the offshore structure's legs can lead to an increase in the internal stresses on structural elements, which could lead to instability or unwanted lateral movement overall. As a result, designers should take this occurrence into account while creating new products. (John B. Herbich, 1984). Various recommendations have been given by the industry's standard practice in order to address the local scour phenomenon during the design stage of the fixed jacket (ONGC, 2008; PETRONAS, 2012; ARAMCO, 2018).

Several studies have been conducted by various researchers, focusing on the scour effect to the pile capacity (Rudolph *et al.*, 2004; Mutlu Sumer *et al.*, 2005; Tseng *et al.*, 2017; Welzel *et al.*, 2019). At the early stage, scour would result in soil loss around the monopile's foundation, hence forming a conical local scour hole. Consequently, it would reduce the embedded pile length of the monopile foundation. Besides, scour may influence the effective unit weight of the soil, depending on the scour depth against the pile diameter (Camp *et al.*, 2004; Qi and Gao, 2019). This happened due to the changing of the overburden stress around the monopile that changes from normally consolidated state to over-consolidated state and the increasing of coefficient of lateral earth pressure at rest (Lin *et al.*, 2010; Li *et al.*, 2020).

Scour decreases the lateral support of the soil, leading to increased overall bending tension in the mound that affects the performance and capacity of the lateral and axial piles (Mostafa, 2012; Li *et al.*, 2018). Pile wall thickness at mudline and other location is normally governed by the combined axial force and bending moment which are computed based on the soil resistance and soil scour (ISO, 2007; Jiang and Lin, 2021). As a result of the various preliminary scour depth, it has a direct impact on the Pile Unity Check, Pile Factor of Safety and Pile-head Displacement (Tseng *et al.*, 2017). This may lead to the unnecessary upsizing pile thickness and pile penetration depth.

In the absence of specific data, current practice for an isolated pile is to use a local estimated scour depth of 1.5 x Outside pile diameter (D), (ISO, 2007). Meanwhile, in the PETRONAS guideline, the minimum of 900 mm or 1.0 x Outside pile diameter (D), whichever greater can be adopted for design purposes (PETRONAS, 2012). Previous researchers have clearly mentioned how the scour phenomena impacts the stability of the structures, especially on its pile capacity. Till date, limited comprehensive study on the scour differences between recommended and actual depth value, and its impact one pile unity check, pile-head displacement, and factor of safety.

Therefore, this study aimed to discover the impact of scouring on pile performance based on the recommended and actual scour depth value of fixed offshore platform. In the next chapter, the development and process of formation scour around the legs of platform will be discussed, followed by the specific design regulation of fixed offshore platform in consideration for the scour depth. Then the research flowchart that illustrated the overall analysis in this study is presented. Finally, a comparison of pile performance was made based on the analysis of static in-place against the recommended and actual scour depth value. Output from this study would assist the designer in the process of decision making at early design stages as well as life extension programs.

1.4 Aims and Research Objectives

The aim of the study was to evaluate the impact of pile scour depth on the existing fixed offshore platform integrity. To achieve this aim, two objectives were set as follows:

i. To analyse the pile performance (i.e., Pile Unity Check, Pile Factor of Safety and Pile-head Displacement) based on the predicted against actual scour depth.
ii. To examine the relation between the scour effect and pile performance in Malaysian waters.

1.5 Scopes of the Study

The study concentrated on fixed jacket offshore platform located in Terengganu (PMO), Sabah (SBO) and Sarawak (SKO) with a water depth ranging from 25 m to 130 m depth. The fixed jacket platform with different number of legs was assessed in a static in-place analysis with pile soil interaction. Selected jacket leg numbers were between 4 legged and 8 legged. It comprised of wellhead, vent and process platform ranging from 5 years to 30 years old.

The platform was modelled and verified using Structural Analysis Computer Software (SACS) suite program version 13.0 and the static in-place analysis with pile soil interaction was performed in accordance to API RP 2A and AISC Working Stress Design. The study reported that the parametric study was carried out to investigate the effect of scour to the pile unity check, pile factor of safety and pile-head displacement.

1.6 Significance of the Study

This study focused on a parametric study of the offshore platform against the recommended and actual scour depth value since limited study has been established. The outcome of this study could be beneficial from both academic and industry perspectives. In terms of academic, the findings from this research enables the development of the correlation between the design scour which is normally adopted from the code and standard against the actual value. This study may also lead to the comparison between the code and standard of practice in this region.

In larger industry perspectives, the study could be beneficial in design optimisation of the fixed offshore platform. Due to the current challenges in the oil and gas industry, cost is the most concerning aspect in determining the survival of the company. On average, an offshore platform is constructed out of 1,000 – 20,000 t or more of steel depending of the type of platforms (Zawawi *et al.*, 2012). Therefore, an optimal design is required without compromising the aspect of safety and strength. The outcome from this study leads towards adopting the realistic and optimum scour depth in the jacket design set as a threshold value for scour in Malaysian waters specifically according to the region.

1.7 Thesis Outline

Chapter 1 describes the introduction of this thesis, which include oil and gas overview in Malaysia, types of offshore structure, challenges in ageing offshore structure, scour, problem statement, aim and objective, scopes, and significance of the study.

Chapter 2 contains the review of the literature study, which include offshore platform, platform degradation and scour to the offshore structure. This is also done to establish the research gap and define the method that was used in the research.

Chapter 3 explains the methodology of the study which includes the introduction of the static in-place analysis and pile soil interaction as well as the effect of scour to the pile unity check, pile factor of safety and pile-head displacement at mudline.

Chapter 4 discusses the results of the selected six platforms from the three different regions. The results contained the pile unity check, pile factor of safety and pile-head displacement for the different scour depth.

Chapter *5* contains the conclusion made based on the parametric study conducted. From the results, it can be concluded that the scour depth has significant impact on the pile unity check, pile factor of safety and pile-head displacement.

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LIST OF PUBLICATION

Publications

1. A. H. Abdullah Sani, M.K. Abu Husain, N.I. Mohd Zaki, N.A. Mukhlas & S.Z.A Syed Ahmad. (2021). Effect of Pile Scouring on Structural Integrity of Fixed Offshore Jacket Structures. Journal of Advanced Research in Applied Mechanics, 86(1), 1–11.