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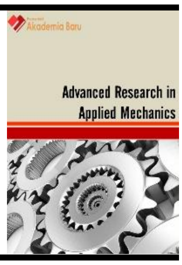

Effect of pile scouring on structural integrity of fixed offshore jacket structures

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ABSTRACT

In general, scour 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 offshore facilities. Codes and standard practices have given various recommendations on the scour depth to be adopted during the initial design stage. Overestimation of the scour depth impacts the pile factor of safety, pile head displacement, and pile unity check, which relates to the economic perspective. Therefore, it is crucial to determine the optimum scour depth adopted in the design stage. This study was performed with the aims to investigate the significant impact of scour depth on the pile performance, to analyse the pile performance based on the design scour against the actual scour, and finally to establish the correlation between scour effect and pile performance. The outcome of this study will assist the industry, especially operators, in reaching the optimum design scour depth.

Keywords:
scour, in-place analysis, pile performance, structural integrity

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1. Introduction

Fixed type platforms are called template type structures, which consist of the jacket or a welded space frame that is designed to facilitate pile driving and act as lateral bracing for the piles. The design of a pile foundation must consider all aspects of the installation and performance of the system [1-4]. The design also should ensure that it has adequate stiffness and strength to withstand the expected load. The fixed steel jacket template stability founded on the piles depends on the (i) bearing or pull out strength, (ii) pile lateral behaviour, (iii) soil liquefaction, and (iv) risk of scouring [5, 6]. Due to criticality of the scour, depth prediction is crucial. Improper judgement may lead to a conservative and uneconomic design [7, 8].

Scour is considered an environmental phenomenon that can impose additional forces on the offshore structure. Removing the seabed soils around the legs of fixed offshore structures can increase the internal forces of structural elements and may lead to overall instability or undesirable lateral movement. This phenomenon should be considered in the design through available guidelines

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[9-11]. Scour has become a serious concern since a strong bottom current with long durations has been observed in many deepwater developments [12, 13].

Various recommendations arise from the industry-standard practices to address the local scour phenomenon during the design stage of the fixed jacket [14-16]. As a result of the various preliminary scour depth, it directly impacts the Pile Factor of Safety (FOS), Pile Head Displacement and Pile Unity Check (UC). To date, no comprehensive study has been conducted on the scour difference between actual and design scour and its impact on the pile unity check, deflection, and safety factor.

Therefore, this paper is aimed to study the impact of pile performance based on the design and actual scour of fixed offshore platforms. In the next section, the development and process of scour formation around the legs of the platform was discussed, followed by the specific design consideration for the scour depth. Then, the research flowchart that illustrates the overall analysis in this study is presented. Finally, a comparison of pile performance is made based on the analysis of static in-place in consideration of design and actual scour depth.

2. Model Specifications and Wave Modelling Analysis

2.1 Scour Development

Scour is the removal of seafloor soils caused by waves and currents. Such erosion can be caused by natural geologic processes or structural elements interrupting the natural flow regime near the seafloor [17, 18]. Scouring effects increase with increased flow speed, turbulence, and increased soil erodability [19, 20]. The two types of scour that commonly occur according to El-Reedy [21] are global and local scour. Global scour affects the areas of piles and usually twice the area covered by the platform, whereas local scour occurs around specific areas of the structure, such as piles. Figure 1 shows the two different types of scouring that generally happen.

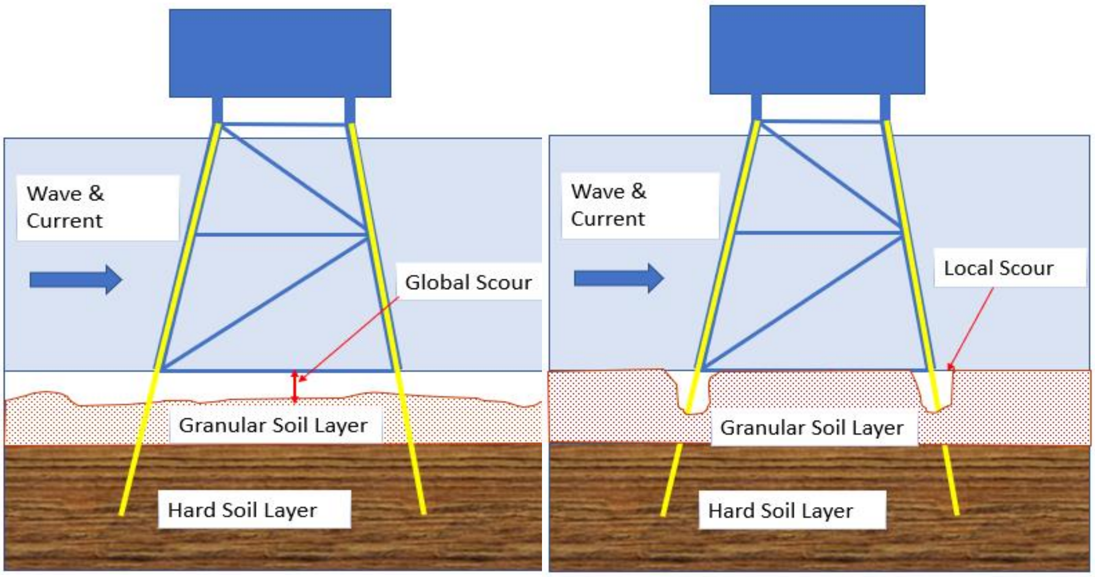

Fig. 1. General Types of Scour

The local scouring mechanism is the product of complex hydrodynamic processes, such as increasing bed shear stress and horseshoe or lee-wake vortices. On the other hand, the global trend can be a mixture of general flow effects, i.e. those created by individual structural elements and the contraction of flow, geologic changes, human activity, meandering and migration, bank erosion, or changes in river flow [22, 23]. It is also important to note that there are substantial overall changes of the seabed triggered by natural causes, such as erosion and accumulation of sediments, which may lead to lowering the bed, thus raising the signs of scouring. Although it is unique to the location, global scouring is essential for designing the base and safety of scour [24]. However, the present study focused only on the local scour at the monopile base, which is the most common scour found in this type of substructure [25].

Several researchers have recently focused on investigating the scouring effect on the pile capacity [26-29]. At the early stage, scour results in soil loss around the monopiles' foundation; hence forming a conical local scour hole. Consequently, it reduces the embedded pile length of the monopile foundation. Besides, it may influence the effective unit weight of soil, depending on the scour depth against the pile diameter [17, 30, 31]. This happens because changing the overburden stress around the monopile would change from a normally consolidated state to an over-consolidated state and the increasing coefficient of lateral earth pressure at rest [32, 33]. Scour decreases lateral support of the soil, leading to increased overall bending tension in the mound and affects the performance and capacity of the lateral and axial piles. Therefore, the impact of scouring on pile performance differs according to the type of soil [34, 35].

2.2 Scour Depth Design Specification

Maximum scour depth is one of the most critical metrics for the construction of a scour-resistant base. The majority of formulations used to assess the predicted optimal scour depth during the structures' life are of a semi-empirical type derived from experimental data [36]. However, as mentioned in De Vos [25], laboratory experiments and field measurements [37-39], as well as measurements in prototype scour holes [40, 41], indicate a good agreement between the empirically expected scour depths and the prototype scour depths. Furthermore, scour depth estimation is generally different for both cohesive and non-cohesive sediments. According to the PETRONAS Technical Standard (PTS), a foundation or jacket shall be designed for a minimum of 900 mm or one pile outside diameter, whichever greater [16]. In comparison, ONGC adopted 1.5 times pile diameter or the depth computed in the approved geotechnical report [9]. As a minimum requirement, 1.5 times pile diameter should be considered in the platform design [11]. Table 1 below shows the comparison of design scours depth adopted based on various standards of practice.

Table 1
Scour depth recommendation

No	*Standard*	*Scour depth [mm]*
1	PETRONAS Technical Standard PTS 11.22.02	Unless otherwise specified, the foundation/jacket shall be designed for a local scour of a minimum of 900 mm or one pile outside diameter.
2	ONGC Structural Design Criteria Part 1	The minimum scour depth around jacket leg/piling shall be the greater than 1.5 times the diameter, or depth computed/stated in approved geotechnical reports.
3	SHELL Standard Engineering Specification SES 10.1	Unless otherwise specified, the foundation/jacket shall be designed for a local scour of a minimum 900 mm or one pile diameter or actual jacket bottom can diameter (whichever is higher).
4	Saudi Aramco Design and Construction of Fixed Offshore Platforms SAES-M-005	Platform design shall consider the effects of scouring. A minimum local scour of 1.50 times the pile diameter shall be used to present scourable seabed materials.

3. Methodology
3.1 Research Flowchart

The research flowchart shown in Figure 2 describes the process of investigating the scouring effect on the pile performance. First, data collection and model preparation was obtained according to the original design of the platform with consideration of scour depth design specification. Then, in parallel, the static in-place analysis was done based on measured scour depth of operational platform after five years based on the existing data and model preparation. In the end, a comparison was made for the result of pile performance in consideration of scouring design depth according to the standard specification, and actual scour depth based on measurement after five years.

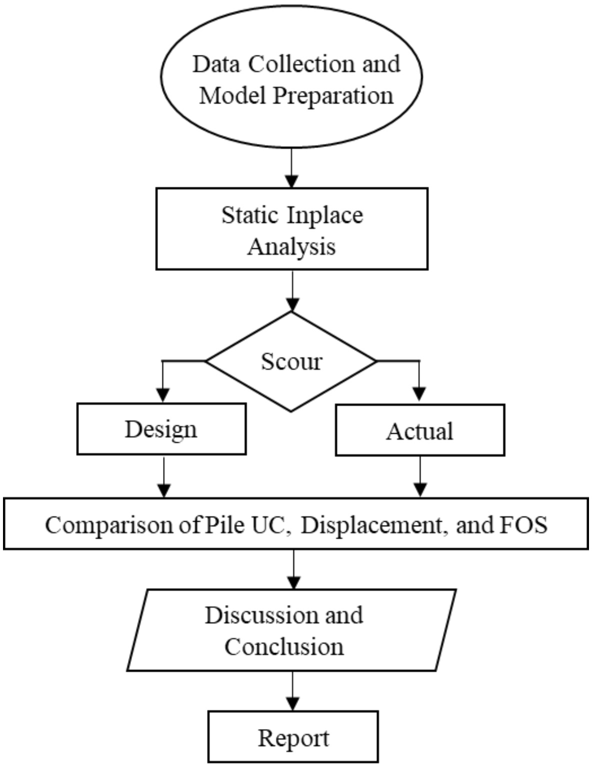

Figure 2: Research Flowchart

3.2 Static In-place Analysis

A static in-place analysis is a structural analysis used to model the action of the structure as similar as possible to the reaction of structure during its service. The typical list of information required before the static in-place analysis can be conducted includes:

i. SACS computer model.
ii. Design basis.
iii. Previous static in-place report.
iv. Latest underwater inspection report.
v. Drawings (AFC or as-built).

This analysis is to investigate the structures' global credibility against untimely failure. Under the ultimate limit state system (ULS), the characteristic capacity is normally taken as the first yield or buckling portion. Ultimate limit state (ULS) criteria are mentioned in various codes that specify structural strength and stability requirements for tubular jacket members to avoid yielding and buckling. The static analysis calculates displacements, strains, stresses, and reaction forces under the effect of applied loads. When loads are applied to a body, the body deforms, and the impact of loads is transmitted throughout the body. In addition, the external loads cause internal forces and responses to equilibrate the body.

Reddy and Swamidas [5] reported that Structural Analysis Computer Software (SACS) had been used. The primary output from the model includes the total load on the structure, typically expressed as base shear, displacement of the deck, and the load's moment and deformations in individual members. Scour is considered by removing the overburden pressure over the scour depth, and local scour is accounted for by neglecting axial and lateral resistance [7]. Figure 3 below describes the procedure to conduct the static in place analysis with pile-soil interaction.

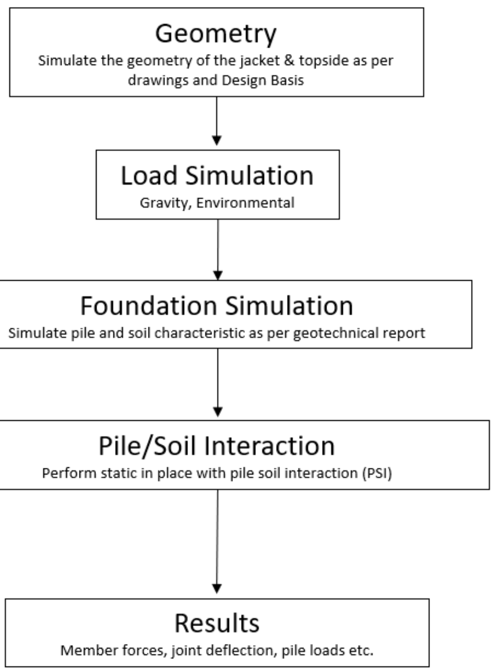

Figure 3: Static Linear Analysis with Pile-Soil Interaction Procedure.

Scour is one of the components and considerations to assess the foundation design under in place conditions. First, the prepared computer model was run by using the design scour value adopted, followed by the next run with the latest scour value from underwater inspection. Pile penetration factor of safety is defined as a ratio between ultimate pile capacity and maximum axial load (Equation 1). The factor of safety should not be less than the specified value in Table 2. The pile unity check was calculated using Equation 2:

$$Factor\ of\ Safety = \frac{Qult}{Maximum\ Axial\ Load + Pile\ selfweight} \tag{1}$$

where Qult is the pile geotechnical capacity

$$\frac{fa}{0.6Fxc} + \frac{\sqrt{f^2bx + f^2by}}{Fb} \leq 1.0 \tag{2}$$

where, *Fxc* stands for critical local buckling stress, *Fb* is the allowable bending stress, while *fbx* and *fby* are bending stress in x- and y-direction, respectively.

Table 2
Pile Penetration Factor of Safety

Load Condition	***Factor of Safety***
Design environmental conditions with appropriate drilling loads	1.5
Operating environmental conditions during drilling conditions	2.0
Design environmental conditions with appropriate producing loads	1.5
Operating environmental conditions during producing operations	2.0
Design environmental conditions with minimum loads (for pull-out)	1.5

3.3 Structural Modelling and Platform Data

The test structure used in this study was a 4-legged pile of fixed offshore platforms located at Peninsular Malaysia water. The pile diameter of the jacket was 1372 mm in a water depth of around 75.7 m. The platforms' design service category was wellhead, and the unmanned category of the design safety factor. Figure 4 provides a visual representation of the structural model.

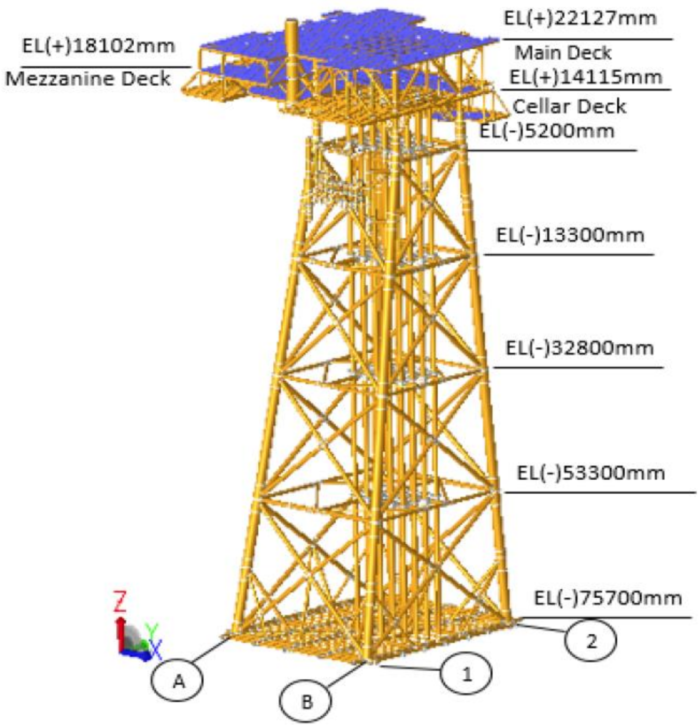

Figure 4: 3-Dimensional View of the Wellhead Platform

4. Results and Analysis

Linear static in-place analysis with pile-soil interaction due to scour was performed on the test structures. The design of scour depth used in compliance with the PTS 11.22.02 guideline corresponded to the actual measured scour depth, as shown in Table 3. The pile-soil input was updated according to the measured scour depth, in which Case A complied with the standard requirement and Case B was the actual measurement. Three load combinations under operating conditions were considered, which were a longitudinal, quarterly and diagonal axis, namely JOAM (0 degrees), JOBM (45 degrees) and JOCM (90 degrees).

Table 3
Scour Depth Case Study

Case	*Description*	*Scour Depth (mm)*	*Ratio (Case B/A)*
A	Design scour depth. Maximum of 900 or 1.0*1372=1372 mm	1372	0.284
B	Actual measured	390	

By considering the values of forces and moment on the pile's head and soil curves, pile load on shaft was determined. A summary of base shear (BS) and overturning moment (OTM) for the jacket with scour depth 390 mm, and 1372 mm was presented in Table 4. The analysis results showed that both base shear and overturning moment increased when the scour depth rose.

Table 4
Summary of Base Shear and Overturning Moment about Mudline

Scour depth	**390mm**		**1372mm**		**Responses ratio**	
Wave and current direction	**Base Shear (kN)**	**Overturning Moment (kN-m)**	**Base Shear (kN)**	**Overturning Moment (kN-m)**	$\frac{BS_{390}}{BS_{1372}}$	$\frac{OTM_{390}}{OTM_{1372}}$
JOAM (0°)	1,156.26	906.10	1,121.94	1,991.50	1.03	0.45
JOBM (45°)	957.34	545.10	943.65	1,387.20	1.01	0.39
JOCM(90°)	820.94	494.90	777.80	1,089.20	1.06	0.45

Table 5
Axial Pilehead Forces, Pilehead Displacement and Unity Check for JOAM

	390 mm			**1372 mm**		
Pile Joint	**Axial Pilehead Forces**	**Pilehead Lateral Displacements (cm)**	**Maximum Unity Check**	**Axial Pilehead Forces**	**Pilehead Lateral Displacements (cm)**	**Maximum Unity Check**
PA1	-812.22	2.56	0.19	-718.68	3.62	0.22
PA2	325.80	2.27	0.16	334.03	3.25	0.19
PB1	-10,895.39	2.76	0.47	-10,912.81	3.82	0.51
PB2	-10,451.85	2.44	0.45	-10,485.87	3.41	0.48

Based on Table 4, the ratio of the responses indicated the utilisation of current base shear and overturning moment from the original estimation.

Focusing JOAM of load combination, the four pile joints were identified. Each joint had different impacts on the factor of safety, displacement of pile head under lateral load and the maximum unity check, as shown in Table 5. A sample calculation was derived as follows:

Pile compression capacity, Q_{ult} = 38000 kN
Pile density, γ = 7850 kg/m^3
Pile weight, w =1056.60 kN
Factor of safety of PA1$_{\text{case A}}$ = $\frac{38000}{(718.68+1056.60)} = 21.41$
Factor of safety of PA1$_{\text{case B}}$ = $\frac{38000}{(812.22+1056.60)} = 20.33$

Table 6
Pile Factor of Safety, Pile Head Displacement and Unity Check Ratio for JOAM

Scour	390 mm	1372 mm	Ratio	
Pile Joint	**Factor of safety**		**Pilehead Lateral Displacements (δ_{390} / δ_{1372})**	**Unity Check (UC_{390}/ UC_{1372})**
PA1	20.33	21.41	0.70	0.86
PA2	27.49	27.33	0.69	0.85
PB1	3.18	3.17	0.72	0.91
PB2	3.30	3.29	0.71	0.93

From Table 6, this study reported a parametric study to investigate the effect of scouring on the pile factor of safety, pile head displacement, and pile unity check. As shown in Figure 5, the pile factor of safety slightly reduced proportional to the scour depth and inversely proportionate with axial pile load. The increase in scour depth did not drastically change the axial pile head forces.

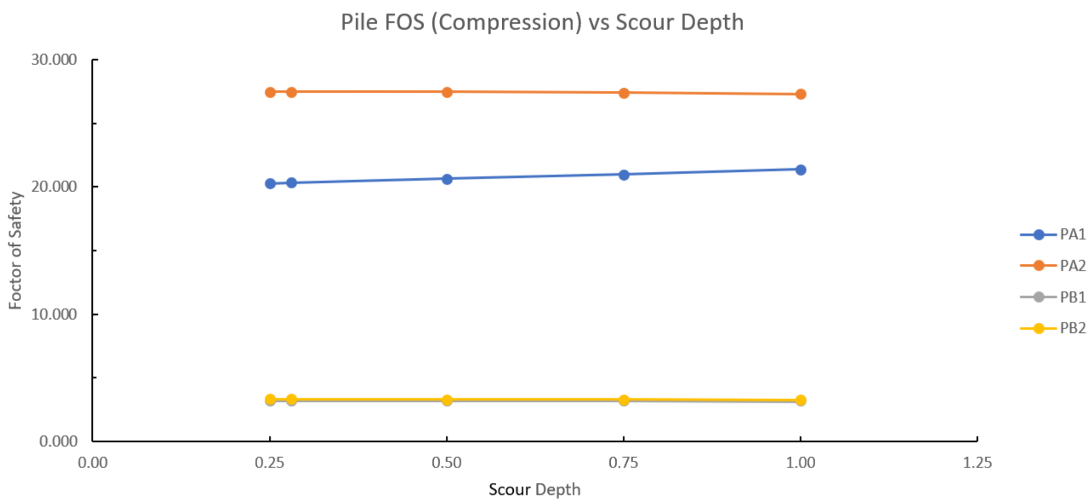

Figure 5: Pile Factor of Safety Versus Scour Depth

To investigate the effect of scour depth on structure stiffness, pile head displacements were extracted from the in-place analysis shown in Figure 6. Pile head displacement had risen proportionally with the increment of scour depth. The increase was due to the loss of lateral support provided by the soil around the pile.

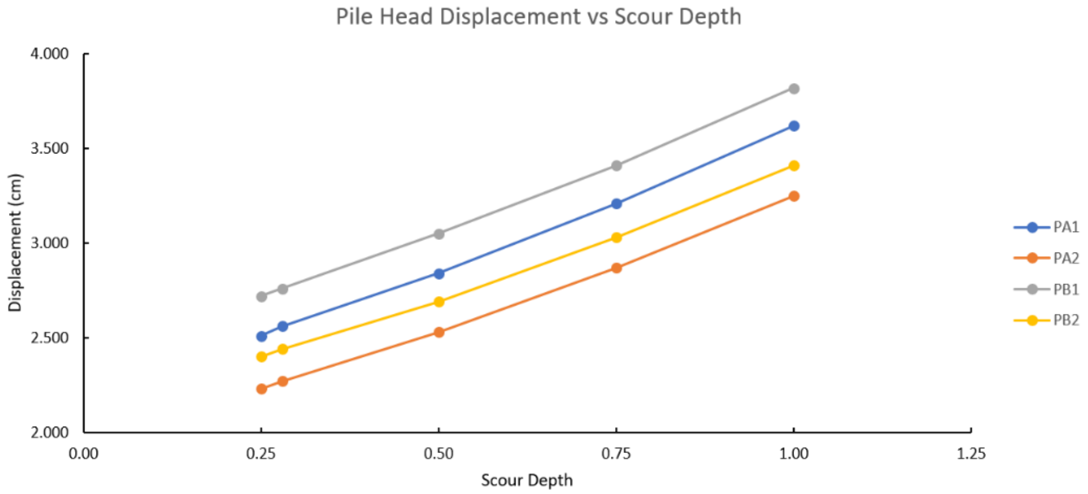

Figure 6: Pile Head Displacement Versus Scour Depth

The analysis results showed that the pile unity checks at the mudline region increased by increasing the scour depth (Figure 7). This was consistent with the overturning moment findings in the previous explanation, whereby the lever arm was increased due to scour.

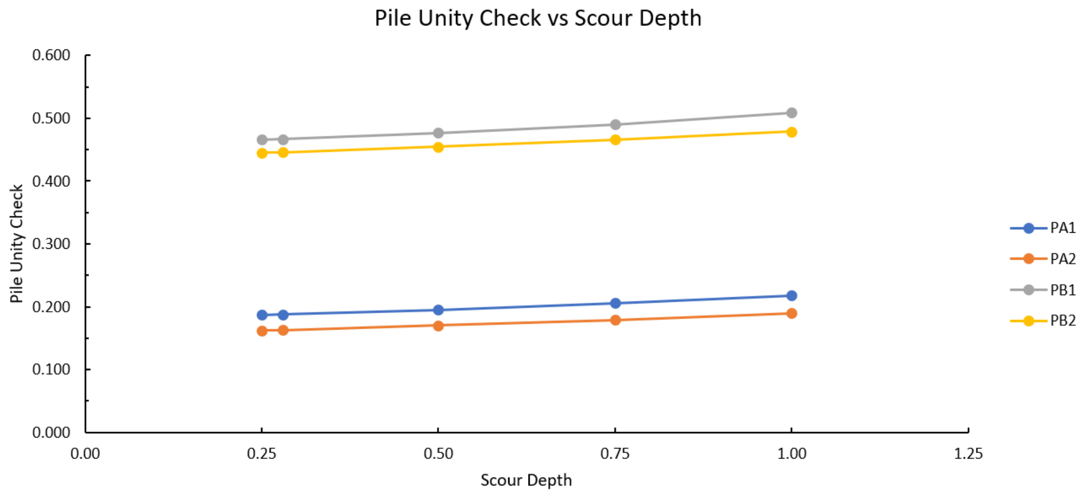

Figure 7: Pile Unity Check Versus Scour Depth

4. Conclusions

This paper has concluded the impact of pile performance based on design and actual scour of the fixed offshore platform has been measured, and the results are summarised as follows:

- An actual measured scour after five years was less than the recommended scour by 71.6% (utilisation of 0.284)

- The pile unity check at mudline and pile head displacement was directly proportional to the scour depth
- The pile factor of safety (FOS) was inversely proportional to the scour depth
- Higher scour value directly impacts the pile UC, pile head displacement, and pile FOS, which led to unnecessary upsizing and deeper penetration.

Therefore, it can be concluded that the depth of scouring design is crucial, and a miss judgment may lead to a conservative and uneconomic design of the offshore structure.

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