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Sensitivity Analysis of Offshore Platform Structures Under Varying Scour Depths

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ABSTRACT

Several offshore platforms operating in the Java Sea have reported experiencing scour at varying depths, raising concerns about the safety and integrity of these structures. Scouring, an erosion phenomenon that occurs around these offshore platform structures due to their presence, is one of the most common issues encountered. The presence of scour can have a significant impact on the safety of these structures. To comprehend the implications of scour on structural safety, sensitivity analysis proves to be an invaluable tool. Sensitivity analysis establishes a relationship between changes in the safety parameters of the structure, obtained through linear analysis, and the depth of scour. By investigating this connection, sensitivity curves can be generated, enabling a conservative prediction of alterations in the strength parameters of the structure due to scour. In this study, a four-legged jacket platform structure underwent linear analysis under storm and seismic conditions using the SACS software. The scour phenomenon was simulated by adjusting the mudline's elevation beneath the structure, modifying the pile coordinates, reducing the length of piles beneath the mudline, and accounting for soil characteristics at each scour depth in the model. The sensitivity analysis revealed that the safety factors of the upper structural components, connections, and piles decrease at varying rates corresponding to each component type as the scour depth of the platform increases. By implementing these sensitivity curves, engineers and operators can make informed decisions regarding the maintenance and retrofitting of offshore platform structures to ensure their ongoing safety and structural integrity in the face of scour-related challenges. This research provides valuable insights into the critical relationship between scour depth and structural safety, enhancing our ability to protect offshore operations in the Java Sea and similar environments.

Keywords: Offshore Platform, Scour, Sensitivity Analysis, Storm, Seismic.

ABSTRAK. Analisis Sensitivitas Struktur Anjungan Lepas Pantai di Bawah Kedalaman Gerusan yang Bervariasi. Beberapa anjungan lepas pantai yang beroperasi di Laut Jawa dilaporkan mengalami gerusan pada kedalaman yang bervariasi, sehingga menimbulkan kekhawatiran mengenai keamanan dan integritas struktur tersebut. Gerusan, fenomena erosi yang terjadi di sekitar struktur anjungan lepas pantai karena keberadaannya, merupakan salah satu masalah yang paling sering ditemui. Keberadaan gerusan dapat berdampak signifikan terhadap keselamatan struktur ini. Untuk memahami implikasi gerusan terhadap keselamatan struktur, analisis sensitivitas terbukti menjadi alat yang sangat berharga. Analisis sensitivitas menetapkan hubungan antara perubahan parameter keamanan struktur, yang diperoleh melalui analisis linier, dan kedalaman gerusan. Dengan menyelidiki hubungan ini, kurva sensitivitas dapat dibuat, sehingga memungkinkan prediksi konservatif terhadap perubahan parameter kekuatan struktur akibat gerusan. Dalam studi ini, struktur jacket *platform berkaki empat menjalani analisis linier dalam kondisi badai dan seismik dengan menggunakan perangkat lunak SACS. Fenomena gerusan disimulasikan dengan menyesuaikan elevasi* mudline *di bawah struktur, memodifikasi koordinat tiang pancang, mengurangi panjang tiang pancang di bawah* mudline, *dan memperhitungkan karakteristik tanah pada setiap kedalaman gerusan dalam model. Analisis sensitivitas menunjukkan bahwa faktor* *keamanan komponen struktur atas, sambungan, dan tiang pancang menurun dengan laju yang berbeda-beda sesuai dengan jenis komponen seiring dengan bertambahnya kedalaman gerusan pada anjungan. Dengan menerapkan kurva sensitivitas ini, para insinyur dan operator dapat membuat keputusan yang tepat mengenai pemeliharaan dan perkuatan struktur anjungan lepas pantai untuk memastikan keamanan dan integritas struktur yang berkelanjutan dalam menghadapi tantangan terkait gerusan. Penelitian ini memberikan wawasan yang berharga mengenai hubungan kritis antara kedalaman gerusan dan keamanan struktur, sehingga meningkatkan kemampuan kami untuk melindungi operasi lepas pantai di Laut Jawa dan lingkungan yang serupa.*

Kata kunci: *Anjungan Lepas Pantai, Gerusan, Analisis Sensitivitas, Badai, Seismik, Integritas Struktural*.

1. INTRODUCTION

Offshore platform structures play a crucial role in supporting oil and gas exploration and production activities in marine environments. However, the presence of waves and currents in offshore areas gives rise to a common issue called scours, which poses a significant threat to the safety of these structures. Consequently, it is essential for the design and analysis of marine structures to consider the impact of scours. To better understand the scour problem, research has been carried out through experimental investigations (Gao et al., 2023; Lyu et al., 2021) and numerical simulations (Baykal, 2017). Furthermore, efforts are underway to mitigate scour-related risks by developing protection systems against scour, as evidenced by ongoing research (Zhang et al., 2021; Petersen et al., 2015).

Regular inspections are conducted on most offshore platforms, and comprehensive data is documented to ensure platform integrity, safety, and compliance with regulations. These inspections often reveal scours with varying depths around the platform legs. Ideally, a prompt assessment can be made to evaluate the platform's safety based on previous analysis results and newly reported scour. This is where sensitivity analysis proves valuable. By extracting the original safety factor of the structure from previous analysis results without or with less severe scour, it becomes possible to estimate the new safety factor after experiencing additional scour using sensitivity curves by estimating the change in safety factors based on sensitivity curves.

Scours can significantly impact the structural integrity of various systems, and extensive research has been conducted to understand their effects. One notable study by (Taheri and Emamverdizadeh beyg, 2018) specifically examines the influence of scour on the reserve strength of fixed jacket platforms. The reserve strength refers to the additional strength beyond what is necessary to support regular and anticipated loads. It is typically designed to handle extreme events like storms and earthquakes. The findings of this study reveal that as the depth of scour increases, the available reserve strength decreases. This research provides valuable insights into the overall reduction in structural safety caused by scours, although it does not determine the sensitivity of individual elements or groups of elements. Furthermore, it is important to note that seismic load effects were not considered in this study. Another related investigation conducted by Sani et al. (2021) focuses on the impact of scouring on the structural integrity of offshore platforms. However, their study primarily concentrates on evaluating the safety factor of the piles and solely considers the effects of storm loads. The research does not report on the consequences of scouring on other structural elements, nor does it account for seismic loads. It is essential to gather further research to comprehensively understand the effects of scours on various structural components and consider the influence of seismic events. Previous studies have employed sensitivity analysis as an approach to develop scour models for bridge piers, as demonstrated by Gaudio (2013). This analytical technique enables a deeper understanding of the relationships between scour depths and their impacts on structural elements.

In this study, sensitivity analysis is used to establish a correlation between the safety factors parameter of the structure and the depth of scour. Through this analysis, a range of sensitivity curves is generated, providing an estimation of the change in the structure's strength parameter. For this study, a four-legged jacket platform structure was utilized as a model. Sensitivity analysis was employed to investigate the impact of varying scour depths on the structure's strength parameter. The modeling and analysis of the structure were conducted using a renowned offshore structural analysis software, SACS, focusing solely on linear analysis in two conditions, namely in-place storm and seismic conditions.

The results obtained from the analysis allowed for the plotting of sensitivity curves, illustrating the reduction in safety factors of the structure's components as the scour depth increases. These curves serve as a valuable tool for estimating the change in the structure's strength parameter in the event of an actual scour phenomenon occurring in a typical platform structure. By leveraging these sensitivity curves, engineers can better understand and address the potential consequences of scouring on offshore platforms, thereby enhancing their safety and integrity. The safety factors for elements and joints are presented as unity check (UC) and for piles as piles safety factor. The unity check (UC) is the ratio of the computed stress value to the allowable stress value. Basically, UC is the inverse of the stress safety factor for structural members. The piles’ safety factor (SF) is the ratio between the allowable axial load to the actual axial load.

In the context of offshore platforms operating in the Java Sea, reports have indicated that some of them are experiencing scouring at various depths, giving rise to concerns about the safety and structural integrity of these installations. Retrofitting an offshore platform comes at a substantial cost. Even conducting a detailed integrity analysis for each offshore platform facing scour-related issues demands a significant amount of time and resources. In contrast, some platforms may possess sufficient reserve strength to remain safe without the need for additional detailed analysis or retrofitting. Therefore, there is a pressing need for a rapid and cost-effective method to estimate the integrity of offshore platforms as a basis for quick and efficient mitigation actions.

This is where sensitivity analysis comes into play. Given the critical nature of offshore platform safety, comprehensive documentation of strength analysis is typically well-maintained. By leveraging data on safety parameters (UC and SF) from previous analyses and combining them with the results of sensitivity analysis, a rapid decision can be made regarding the safety status of an offshore platform experiencing scour (be it new or additional scour depth). This determination helps decide whether further detailed analysis is warranted or if plans for retrofit should be prepared. In severe cases, it can even serve as the basis for suspending platform operations before a serious hazard arises due to structural or foundation failure.

2. METHODOLOGY

The sensitivity analysis was performed on jacket type offshore platform that consists of steel jacket, piles and decks (Chakrabarti S.K., 2005). The sensitivity analysis in this study was performed in the following steps:

a. Select a representative platform model for sensitivity analysis.
b. Modify the model to represent the scour condition with varying depths. The modification is described in more detail in Section 3.
c. Perform structural analysis and safety factor calculations following (API RP2A WSD 2007) code. Linear analysis was performed on the model. Sensitivity analysis for storm and seismic conditions was performed to investigate the effect of varying scour depth on the safety factors of structural members/joints and piles. The results of the sensitivity analysis were a set of curves that relate the scour depth to the change in the safety factor of members/joints and piles.

To simplify the analysis, the sensitivity analysis results were grouped into member types as follows:

a. Main deck member: members in the top-level deck.
b. Cellar deck member: members in the lower-level deck.
c. Deck leg: vertical members between the main and cellar deck.
d. Deck truss: diagonal and vertical truss members between the main and cellar deck.
e. Diagonal bracing: diagonal bracing of the jacket.
f. Horizontal frame: horizontal bracing of the jacket.
g. Leg: the main tubular member that contains the piles.
h. Pile under the jacket: piles under the jacket are sections of the pile that originally penetrate the soil, starting under the jacket members' lower ends.

i. Pile inside jacket: piles extension above seabed that driven inside the jacket legs.

2.1 Platform Model

A four-legged jacket platform was used as a study model in the sensitivity analysis that was conducted as shown in Figure 1. Piles are not shown in the Figure. The platform has four legs, 2 decks and 7 conductors. The platform's main elevations is shown in Table 1.

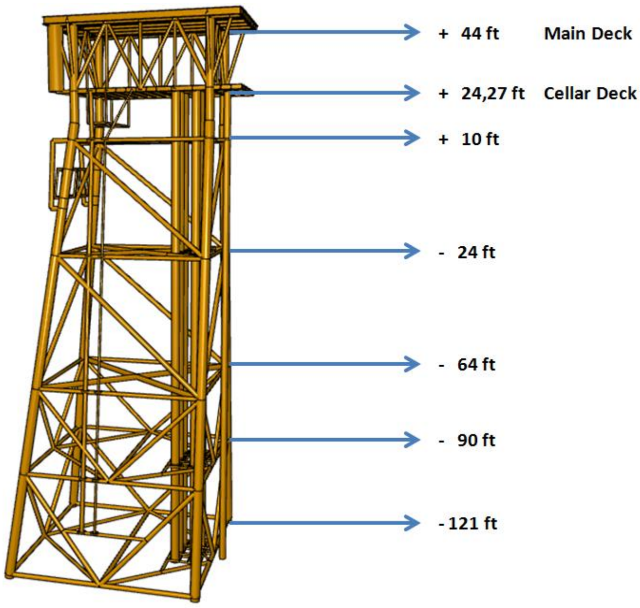

Figure 1. Jacket type offshore platform model

Table 1. Structure load

Platform Component	Elevation
Main deck	(+) 44' – 0.000"
Cellar deck	(+) 24' – 3.313"
Sub cellar deck	(+)15' – 5.000"
Jacket walkway	(+)10' – 0.000"
Boat landing	(–) 6' – 0.557"
Mudline	(–)121' – 0.000"

This platform is used as a drilling and production facility. The main deck is used as the operational area and the cellar deck is used as the equipment placement.

Structure model and analysis were done using SACS software. The calculations were conducted with the assumption that the structure and the piles are linear systems while the soil behavior is non-linear.

For reference, Figure 2 displays a simplified model featuring only the jacked legs. The numbers depicted serve as joint identifications for the primary jacket joints. Identification for members connecting *Joint*$_i$ and *Joint*$_j$ is denoted as *Joint*$_i$ - *Joint*$_j$. We have chosen to present solely the joint and member identifications for the legs because scour depth has a relatively insignificant impact on the safety of other structural members not connected to the leg.

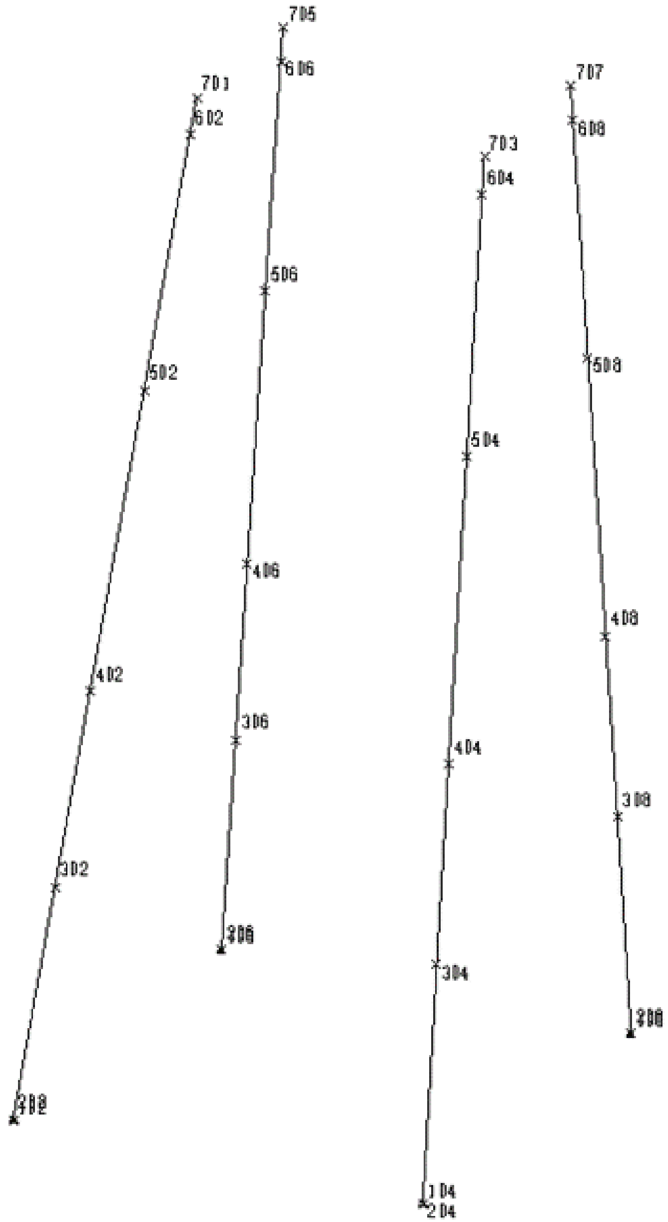

Figure 2. Jacket leg joints numbering

2.2 Environmental Data

For the study case's purpose, it was assumed that the structure was placed in a water area with the environmental data as presented in Table 2.

Table 2. Environmental data

Mean Sea Level (MSL)	121 ft
Highest Astronomical Tide (HAT)	3.8 ft
Storm Tide	0.5 ft
Storm Wave Height (H)	27.3 ft
Storm Wave Period (T)	9.3 Sec.
Storm Wind Speed	63 mph

2.3 Dead Loads and Live Loads

Dead loads caused by the structure’s load were calculated automatically by SACS software based on the dimension and the density of the element. Other dead loads which were not calculated automatically by the software were accounted as external loads working on the structure’s nodes or elements. Table 3 shows the dead loads and live loads which were assumed borne by the structure.

Table 3. Structure load

Loads	**(kips)**
Substructure dead weight (including piles above mudline)	759.1
Deck dead weight	89.0
Boat landing weight	4.9
Equipment and live load on deck	275.0
Main deck bulk load	119.7
Cellar deck bulk load	88.2
Main deck live load with workover rig	28.1
Cellar deck live load	29.4
Workover rig at well #2	420.0
Workover rig at well #5	420.0
Workover rig at well #6	420.0
Workover rig at well #7A	420.0
Workover rig at well #7B	420.0

2.4 Environmental Loads

Forces caused by wave and current were calculated automatically by SEASTATE module in SACS software system. The environmental loads were accounted for from eight directions to analyze the structure’s strength at the critical level in both operating and storm conditions. The current speed was added to the speed of the water particle which was caused by the wave. The wind forces were calculated using the wind speed data assumed for both operating and storm conditions. The drag coefficient, C_d, and inertia coefficient, C_m, were taken according to the (API RP2A 2007) standard, which is: C_d = 0.65 and C_m = 1.6 for smooth surfaces; or C_d = 1.05 and C_m = 1.2 for rough surfaces. The wave forces were calculated using the 5th-Stoke Wave Theory which the software has provided.

2.5 Load Combinations

The load combinations applied to the structure's model for both storm and seismic conditions are the combination of dead load, live load, environmental load (wind, wave, and current load) and seismic load as specified in (API RP2A WSD 2007).

2.6 Scour Model

The scour depth variation considered in this study is based on reported scour depth observed during Inspection and from previous studies of scour model and evolution. (Matutano et al., 2013) present a comprehensive list of formulations developed to predict the maximum scour depth. These formulations consider various flow conditions, including steady current, waves, and combinations of steady current and waves. Based on these formulations, the estimated scour depth can reach up to 2.5 times the diameter of the pile. Harris et al. (2010) conducted a study on the development of scours over time, revealing that the scour depth reaches a balanced condition of approximately three to four meters in shallow water and up to six meters in deep water. Based on reported scour depth and previous studies, scour depth variations from zero to 10 feet (3 meters) are considered.

The following are the modifications that should be done to the platform's model to represent the scouring phenomenon in the structure's model:

- The joint pile stubs in the model represent the border between the pile at the upper side and lower side of the mudline was moved according to a certain scour depth level.
- The mudline height in the model was lowered according to a certain scour depth as
- The soil parameter data in the Pile-Soil Interaction (PSI) module were removed until the new mudline elevation level.
- The depth of soil layer data in the PSI module, measured from the initial mudline location, was modified to suit the new mudline elevation location.
- The piles' length in the PSI module, which is the model of the piles located below the mudline, should be reduced according to the scour depth.

Figure 3 shows scour model on the platform's model where only the pile section below the jacket elevation is shown. The springs represent the soil stiffness.

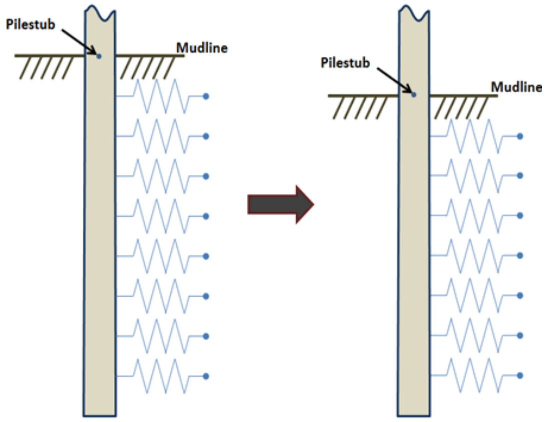

Figure 3. Illustration of scour model on the platform's model, showing only pile below the jacket elevation

3. RESULTS AND DISCUSSIONS

The results of the analysis conducted are elements and joints' unity check (UC) and piles' safety factor (SF). The sensitivity curves show the relationship between the elements and joints' UC and piles' SF changes as function of scour depths.

3.1 In-place Storm Condition

The following is the sensitivity analysis results of UC and piles' SF for 100-year return period storm condition.

For scour depth from 0 to 10 feet with one-foot increments, all jacket and deck members and joints had been checked for 100-year storm condition according to the (API RP2A WSD 2007) standard. Maximum members and joints' UC for 100-year storm conditions were plotted as a function of scour depth. To avoid erratic results, only member groups with UC larger than 0.25 were included in the plots. The UCs were normalized by using values for conditions without scouring as 100%. The sensitivity curves from the analysis are presented for member groups, consecutively from Figure 4 to Figure 15.

3.1.1 Member and Joint's UC

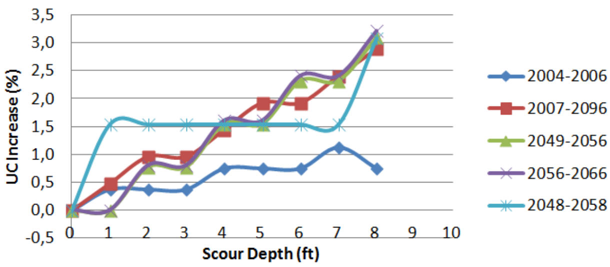

Figure 4. Normalized UC change for the main deck in storm condition

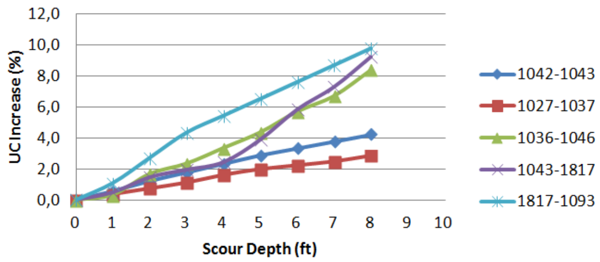

Figure 5. Normalized UC change for cellar deck in storm condition

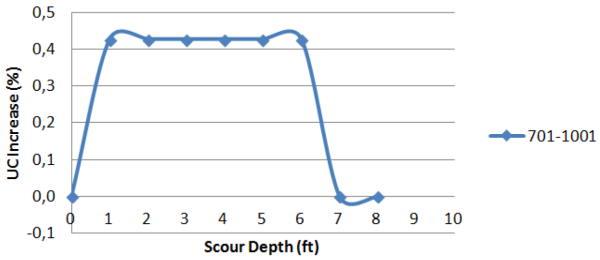

Figure 6. Normalized UC change for deck leg in storm condition

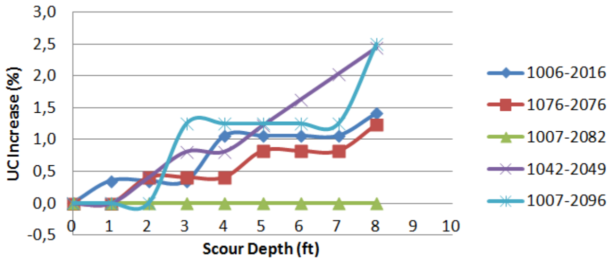

Figure 7. Normalized UC change for deck truss in storm condition

Figure 4, Figure 5, Figure 6, and Figure 7 show that members in the decks level are not sensitive to scour for a 100-year return period storm. Up to 9 feet of scour depth, the UCs increase by less than 5% for all members above the cellar deck and by up to 10% for all members in the cellar deck level.

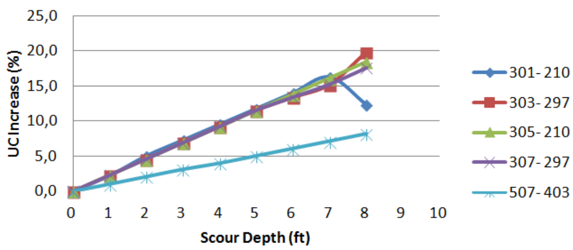

Figure 8. Normalized UC change for diagonal bracing in storm condition

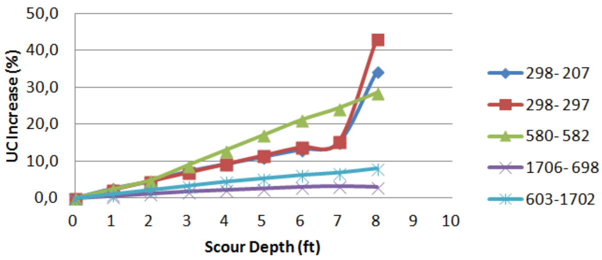

Figure 9. Normalized UC change for horizontal frames in seismic condition

Figure 8 and Figure 9 show that both diagonal and horizontal bracing are sensitive to scour for 100-year return period storm. Up to 9 feet of scour depth the UC of the members increases almost linearly as a function of scour depth. The UC increases up to 20% and 40% for diagonal bracing and horizontal bracing, respectively.

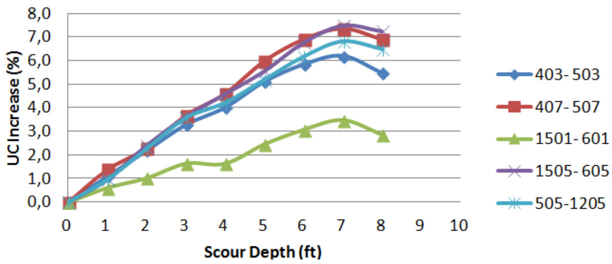

Figure 10. Normalized UC change for leg members in storm condition

Figure 10 shows that leg members are not sensitive to scour. This is due to the condition that the legs do not support the platform structure weight. The main functions of the legs are to facilitate the installation of the piles and to transfer forces from piles to diagonal and horizontal bracing. Up to 9 feet of scour depth the UC of the members increases below 8%.

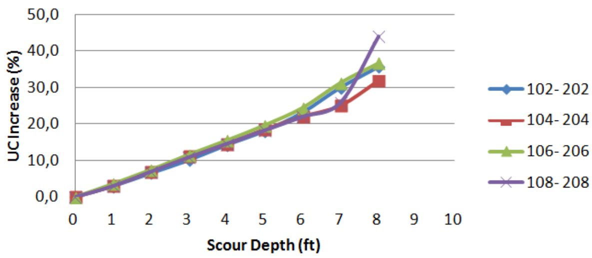

Figure 11. Normalized UC change for pile under jacket in storm condition

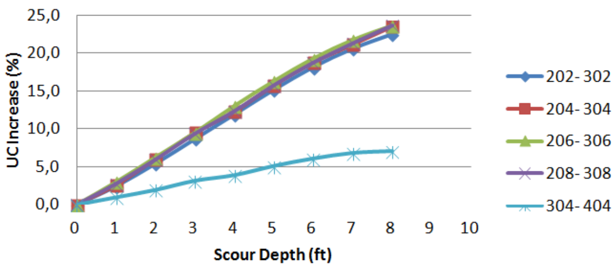

Figure 12. Normalized UC change for pile Inside jacket in storm condition

Figure 11 and Figure 12 shows that both pile members inside and under the jacket are sensitive to scour for 100-year return period storm. Up to 9 feet of scour depth the UC of the members increases almost linearly as a function of scour depth. The UC increases up to 20% for pile members inside the jacket. The most sensitive members are those pile members under the jacket that are exposed and lost lateral support from the scoured soil. The UC increases up to 40% for pile members under the jacket and jumps significantly for scour depths more than 7 feet.

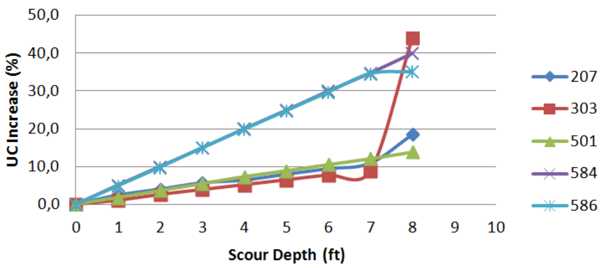

Figure 13. Normalized UC change for joint in storm condition

Figure 13 shows that joints are also very sensitive to scour for 100-year return period storm, especially those joints between jacket legs and bracings. Up to 9 feet of scour depth, the UC increases up to 40% for joints and jumps significantly for scour depths more than 7 feet.

3.1.2 Pile Safety Factor

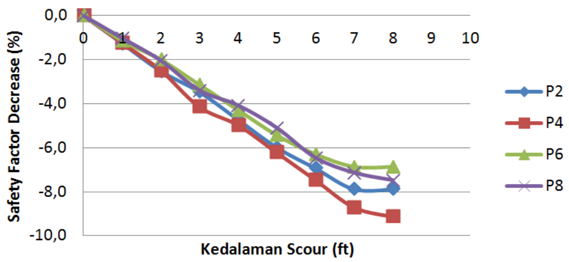

Figure 14. Normalized change for pile in compression safety factor in storm condition

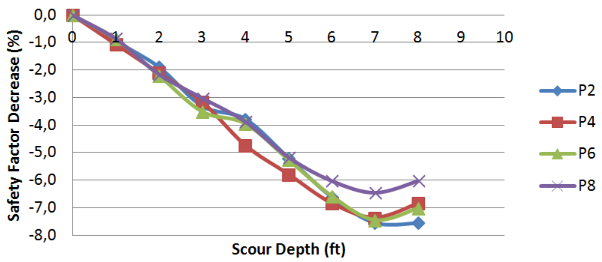

Figure 15. Normalized change for pile in tension safety factor in storm condition

Figure 14 and Figure 15 show that piles both in tension and compression are not sensitive to scour for 100-year return period storm. Up to 9 feet of scour depth, the safety factors of the pile decrease by less than 10% for both tension and compression load.

3.2 Seismic Condition

The following is the sensitivity analysis results for seismic condition. In this sensitivity analysis, only ductility level earthquake analysis with 800-year return period had been performed according to (API RP2A WSD 2007) standard.

For scour depth from 0 to 10 feet with one-foot increments, all jacket and deck members and joints had been checked for seismic conditions according to the (API RP2A WSD 2007) standard. Using the same procedure as for storm conditions, UC for members and joints were plotted as a function of scour depth. The sensitivity curves from the analysis are presented consecutively from Figure 16 to Figure 25.

3.2.1 Member and Joint's UC

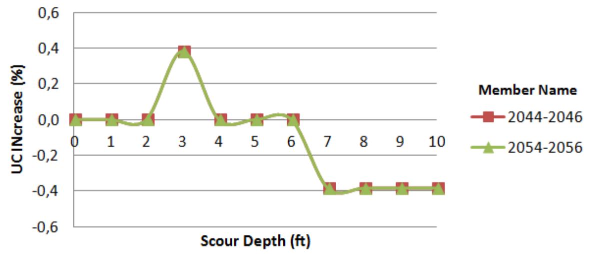

Figure 16. *Normalized UC Change for Main Deck in Seismic Condition*

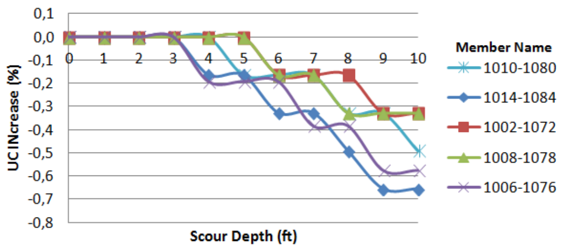

Figure 17. Normalized UC change for cellar deck in seismic condition

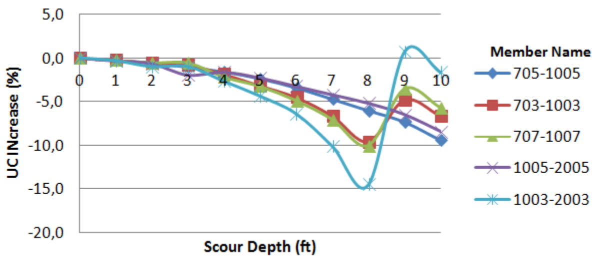

Figure 18. Normalized UC change for deck leg in seismic condition

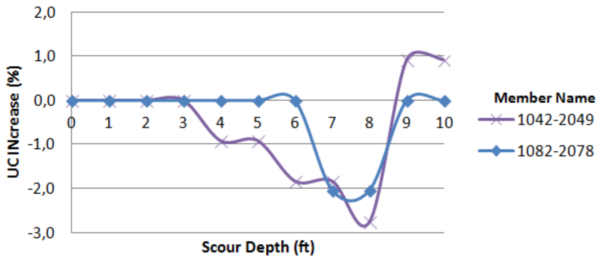

Figure 19. Normalized UC change for deck truss in seismic condition

Figure 16, Figure 17, Figure 18, and Figure 19 show that members at the deck level are not sensitive to scour for seismic conditions. Up to 9 feet of scour depth, the UCs increase by less than 5% for all members above the cellar deck and above. In most cases, the UC even decreases. The decrease in the UCs as scour depth increases is due to decrease in seismic load caused by a decrease in the stiffness of the platform structure and hence an increase in the structure's natural period.

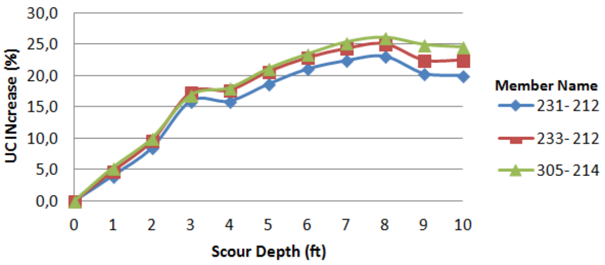

Figure 20. Normalized UC change for diagonal bracing in seismic condition

Figure 20 shows that diagonal bracing members are sensitive to scour in seismic condition. Up to 9 feet of scour depth the UC of the members the UC increases up to 25%. The UC increase rate is slowing down for higher scour depth due to a decrease of the seismic load caused softening of platform structure as scour depth increases and hence increase in structure natural period.

Sensitivity analysis results for horizontal bracing and jacket legs are not presented since the UC of both member groups is too small (less than 0.25) and not considered critical.

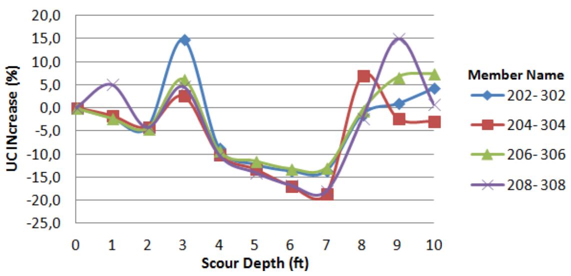

Figure 21. Normalized UC change for pile under the jacket in seismic condition

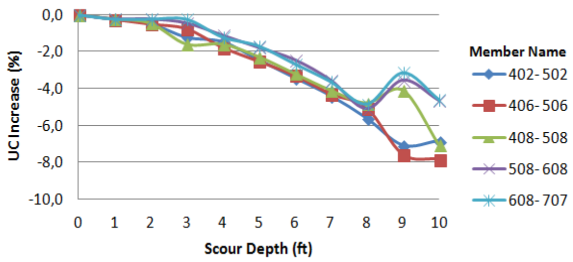

Figure 22. Normalized UC change for pile inside jacket in seismic condition

Figure 21 and Figure 22 shows that both pile members inside and under the jacket are sensitive to scour for 100-year return period storm. Up to 9 feet of scour depth the UC of the members increases almost linearly as a function of scour depth. The UC increases up to 20% for pile members inside the jacket. The most sensitive members are those pile members under the jacket that are exposed and lost lateral support from the scoured soil. The UC increases up to 40% for pile members under the jacket and jumps significantly for scour depths more than 7 feet.

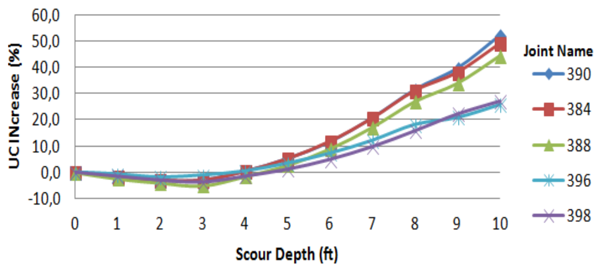

Figure 23. Normalized UC change for joint in seismic condition

Figure 23 shows that joints are also very sensitive to scour for seismic conditions, especially those joints between jacket legs and bracings. Up to 9 feet of scour depth The UC of scour depth, the UC increases up to 50% for joints. Interestingly, joints UCs are not sensitive to scour up to 5 feet scour depth.

3.2.2 Pile Safety Factor

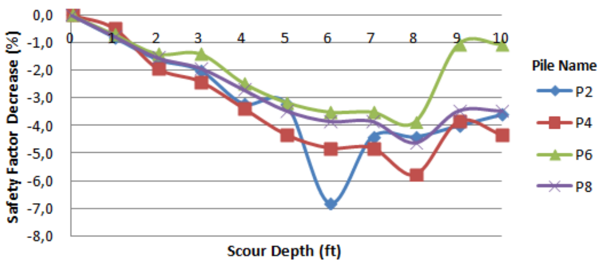

Figure 24. Normalized change for pile in compression safety factor in seismic conditions

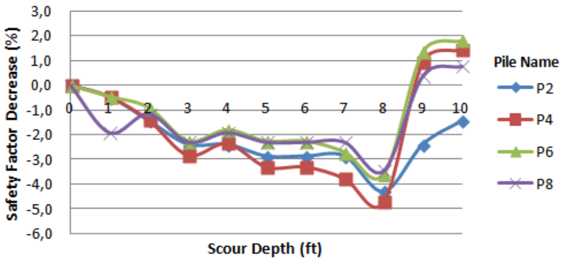

Figure 25. Normalized change for pile in tension safety factor in the seismic condition

Figure 24 and Figure 25 show that piles both in tension and compression are not sensitive to scour for seismic conditions. Up to 9 feet of scour depth, the safety factors of the pile decrease by less than 7% for both tension and compression load. Similar to observations for storm conditions, the axial safety factors of the pile is not sensitive to scouring since the scour only removes the soft top layers of the soil that does not contribute significantly to the pile's axial bearing capacity. For cases where the axial safety factor increases, this is due to the softening of the platform structure as scour depth increases.

4. CONCLUSIONS

Based on the sensitivity analysis conducted for a typical offshore platform following the (API RP2A WSD 2007) criteria for storm and seismic conditions, the following conclusions can be drawn:

1. For storm conditions, the results can be summarized as follows:
   a. All elements of the cellar deck and those above it are not particularly sensitive to scouring. In this group of elements, the increase in UC remains below 10% for scour depths up to 9 feet.
   b. The group of elements that are sensitive to scour includes diagonal bracing, horizontal bracing, piles, and joints. In this group of elements, the increase in UC can reach up to 50% for scour depths up to 9 feet.
   c. The axial bearing capacity safety factor of the foundation is not very sensitive to scour. The decrease in the axial bearing capacity safety factor for piles remains below 10% for scour depths up to 9 feet.
2. For seismic conditions, the grouping of elements that are sensitive and not sensitive to scour is similar to that of storm conditions. When comparing storm and seismic conditions, it is evident that storm conditions are more critical and sensitive to scour compared to seismic conditions. The impact of scour on the structure is less pronounced in seismic conditions because scour leads to structural softening, which in turn increases the structural period and decreases seismic forces as the scour depth increases.

3. The results of the sensitivity analysis yield sensitivity curves, which can be readily employed for the swift estimation of changes in the safety factor concerning both the structure and its foundation in correlation to scour depth. These sensitivity curves serve as a valuable tool, providing engineers and operators with a clear and efficient means of assessing the structural and foundational safety of offshore platforms operated in the Java Sea and similar environments facing scour-related challenges. By examining the trends depicted in these curves, it becomes possible to make informed decisions regarding the need for further evaluation, retrofitting, or reinforcement, thereby ensuring the continued integrity and security of these vital installations.

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