Evaluation of factors contributing to wave-in-deck using pushover analysis for fixed jacket structures

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Abstract. Wave in deck (WID) phenomenon of a wave hitting on the topside for fixed jacket platforms at shallow water condition has been reported as a notable risk to the workability and reliability of these structures. When hydrocarbon from the seabed is extracted for an extended period of time, there might be a reduction in pressure, which allows subsidence to happen. A platform experiencing subsidence promotes the decrease in air gaps, which eventually allows the waves to attack the bottom decks. The impact of the WID generates additional loads to the structure and therefore increases the values of the moment arms. Higher moment arms trigger instability in terms of overturning, which eventually decreases the reserve strength ratio (RSR) values of the structure. The mechanics of WIDs, however, are still not well understood and have not been fully incorporated into the design codes and standards. Therefore, there is a need to revisit the current design codes and standards for platform design optimization. This paper aims at evaluating the effect of RSR values due to WID on four-legged jacket platforms in Malaysia. Base shear values with regards to calibration and modifications of wave characteristics are obtained by numerical simulations. Correspondingly, pushover analysis was conducted to retrieve the RSR. The effects of the contributing factors, namely wave height, wave period, and water depth with regards to the RSR and base shear values, are expected to be analyzed and thoroughly discussed. The work illustrated in this paper is important in optimizing the design life of the existing and aging offshore structures. Outcomes of this research are expected to provide an additional evaluation of the WID mechanics and in return, contribute to the current mitigation strategies in managing the issue.

1. Introduction
The global demand for energy and power, particularly fossil fuel, is constantly shooting up despite the economy breakdown happening worldwide. Oil and gas specialists have since been improving their engineering techniques on the designs of offshore platforms, for instance, to create economical and sustainable ways to conduct their exploration and production activities. This is due to the fact that these structures are often subjected to high flow velocities induced by waves and currents. Regardless of technology advances, destructions of many offshore structures happen over the years resulting in loss of lives and extreme sea pollution. It was reported that one of the common issues that happened on these aging jacket platforms is the wave slamming on the topside deck or namely the wave-in-deck (WID) effect. WID occurs due to events, e.g., the reservoir compaction, increment of topside weight or operation loads, etc., which results in the subsidence of seabed. Eventually causing a negative air gap and allowed the wave slamming on the deck structure. This effect is causing losses, fatality, and injuries, e.g., incidents of COSL innovation [1, 2].
According to the study, the main concern of global failures includes structural failure, capsizing or sinking, and positioning system failure, which are normally due to physical and technical events [3]. Basically, structural failure happens when the resistance is lesser than the load effect. The study also mentioned that WID had been acknowledged as a concerning phenomenon relating to the decrease of air-gap due to subsidence of seabed [4]. Air-gap, which is the space allocated between the lowest deck of the structure and the mean sea level (MSL), has a minimum requirement of 1.5 meters for fixed offshore structures. Although it is a common practice to maintain a positive air gap as acquired by codes and standards, it is found that this allowable space is not reliable due to different offshore structures experiencing various environmental circumstances. Similarly, the study claimed that this is caused by the inability to obtain sufficient data in the design stage, as these data are not recorded during ‘rare’ environmental events, especially in the old days [5]. In addition to that, uncertainty in environmental conditions is one of the very significant challenges in the offshore industry. It can be a hazard to human life and the workability of the structure. In the design of offshore structures, gravity load, and environmental loads, particularly the wave load, are the major components that need to be considered. A variety of methods and theories were introduced and developed to focus on the structural integrity analysis of offshore platforms due to environmental loads [6]. A global approach, which provides a global load based on the exposed area, may affect the integrity of the platform as a whole. Global and detailed approaches have been established in previous years. The API, Shell and DNV Statoil methods are among the global approaches used up till today. Additionally, local failures can be approached by using Kaplan, Chevron and Amoco methods. Interestingly, the approach has been recommended by HSE for the purpose of investigating the importance of wave-in-deck load on the offshore platform [7, 8].

There are various general acceptance criteria provided in many guidelines. According to the International Standard (ISO), the RSR acceptance criteria shall be more or equivalent to 1.85. As for the American Petroleum Institute (API), RSR values of 1.6 and 0.8 are required for high sequence platform and low sequence platform consecutively. They have also indicated that the platform is likely to fail when RSR is below 1.0. However, according to the structural global ultimate strength analysis report, the minimum acceptance criteria for unmanned platforms shall be more than 1.32 and 1.5 for manned platforms. Pushover analysis is an efficient approach to evaluate the non-linear behavior and ultimate capacity of offshore structures [9]. Many software and methods have been introduced to demonstrate the platform’s strength and ability to withstand the ultimate strength loading. The study carried out a study using both global and local approaches to find realistic time-load histories for jacket structures in the North Seas. It is found that the deeper the water, the more displacement occurs at the deck level. The issue of reliability and integrity of aging platforms have been addressed by using the Global Ultimate Strength (GUSA) Method [10]. They have concluded that the wave crest, according to API, is found to be higher than the results produced by the numerical simulation.

Further, with a high value of RSR and lower the probability of failure (POF) than the acceptance criteria, hence the platform is safe for an extension. On the other hand, MSL Engineering Ltd presented a study for the Health and Safety Executive (HSE) to determine the contribution of air-gap and effects of inundation of a jack-up platform with a storm return period of 10,000 years [11]. The platform was subjected to two environmental load factors and two water depths simultaneously. Results obtained from the comparison appeared that Statoil’s overturning moment is merely 70% of MSL’s prediction. With increasing wave height, the large vertical force was discovered using the MSL method, covering nearly 50% of the jack-up platform. Additionally, the environmental load factors of 1.25 and 1.15 were found only to produce 10% differences. Meanwhile, a difference of approximately 0.8 m in inundation levels showed significant effects on global loads concerning total base shear, overturning moment, and RSR value. Investigations are revealed that the current pushover analysis utilizing RSR parameter and a storm return period of 100 years cannot determine the real failure against wave loaded [12]. They claimed that RSR values in offshore codes are disputable and not proficient in the safety requirements. Therefore, Collapse Wave Height (CWH) was introduced to substitute the RSR value.

2. The numerical simulation
In this paper, numerical simulation was used to assess the impact of WID on jacket structures. Methods to obtain factors contributing to WID are discussed, including a systematic parametric study on wave force
together with the jacket model specifications. Two jacket platform models, as shown in figure 1, were selected in this study for comparison with the descriptions of each platform presented in table 1.

The WID event was simulated in the strength assessment software for offshore structural. An assessment was performed to evaluate the air gap and validate the data input prior to the simulation. Generally, from the simulation, the properties i.e., the base shear (BS), and RSR for design, collapse and in WID conditions were obtained, where RSR is given as:

\[
RSR_{\text{collapse}} = \frac{BS_{100}}{RS_{\text{collapse}}} \quad (1)
\]

Modified pushover analysis was repeated for conditions, i.e., design, collapse, and WID, until the target achieved. The results from the analysis were used to further analyze in order to quantify the effects or the significance of WID conditions, as a function of wave height.

![Platform A](image1.png)  ![Platform B](image2.png)

**Figure 1.** Two jacket platform models.

| Description                              | Model A   | Model B   |
|------------------------------------------|-----------|-----------|
| Water Depth (m)                          | 75.40     | 93.99     |
| Air Gap at Collapse Condition (m)        | -2.93     | -6.80     |
| RSR Collapse                             | 3.89      | 4.20      |
| No. of Legs                              | 4         | 4         |
| No. of Piles                             | 4 (1372 mm Ø) | 4 Main Piles (1067 mm Ø) |
|                                          | 2 Skirt Piles (1372 mm Ø) |
| Platform Function                        | Wellhead  | Living Quarters |
| Design Category                          | Unmanned  | Manned    |
| HAT (m)                                  | 1.00      | 0.90      |
| LAT (m)                                  | -1.30     | -1.20     |
| Storm surge (m)                          | 0.60      | 0.60      |
| Subsidence (m)                           | 3.00      | 5.60      |
| Wind Load (kN)                           | 460       | 257       |
| Design Wave Height (m)                   | 12.60     | 12.60     |
| Associated Wave Period (s)               | 11.80     | 11.70     |

**3. The structural responses due to wid**

In this section, simulation results for Platforms A and B were presented, and discussion was given to the effects of changing different parameters such as wave height, wave period and water depth. From figure
2, it could be seen that the base shear increases as wave height increases. Comparing the WID condition and the design condition, the design base shear comprises of only 26% of the total base shear at WID following the average of 10 m wave height increment. Therefore, it can be seen here that it is important to consider the wave-in-deck load in the RSR values, especially at the design stage for safety purposes. On the other hand, as shown in figure 3 also, it can be seen that the RSR value at WID condition was found to be much lower as compared to the RSR at collapse condition, with a difference of 2.78 for both water depths. It can be noted that the results of RSR values at WID, which stand at 1.1 and 1.06 are found to be below the minimum acceptance criteria for the unmanned platform that 1.32. This could be due to an indication of weak areas or member failures due to the wave and current force.

![Figure 2](image_url)  
**Figure 2.** Base shear with respect to wave heights for Platform A.

![Figure 3](image_url)  
**Figure 3.** Reserve Strength Ratio (RSR) with respect to wave heights for Platform A.

![Figure 4](image_url)  
**Figure 4.** Base shear with respect to wave heights for Platform B.
Figure 5. Reserve Strength Ratio (RSR) with respect to wave heights for Platform B.

It can be seen from the figures 4 and 5 that the value of RSR decreases whereas the base shear value increases as wave height increases, which is in compliance to what observed in Platform A. Looking back at the structural global ultimate strength assessment report, the RSR value at WID for both water depths i.e. 3.59 for Platform A and 3.57 for Platform B shown in figure 5 seems to satisfy the minimum acceptance criteria for manned platform. In other words, this platform can still be assumed to be on the safe side despite WID occurrence. Further analysis i.e., air gap analysis and reliability check, are proposed to be conducted before any conclusions, can be made to determine the safety of the jacket. Additionally, if looked closely, the value of RSR at WID condition does not vary much from the collapse condition, with an average difference of 17.5%. This could be due to the fact that there are two additional skirt piles supporting the structure. Besides that, the structural forms may vary depending on the site installation condition. As a result of the assumed stronger foundation system, it is expected that with different loading patterns imposed on the foundation by the two conditions; collapse and WID, different load distribution paths were created conjointly. However, it is believed that the actual reasoning behind these results needs to be investigated further.

Comparing the two platforms, i.e., figure 2 and 3 for Platform A, also for figures 4 and 5 for Platform B, it can be seen that the relationships between water depth and the RSR values do not show much difference with the increment of water depths. The RSR values difference of 0.05 and 0.24 were observed in Platforms A and B, respectively. This can be explained by the fact that the water depth modification only involves a difference in tide heights. Regardless of the small difference observed, it is still worth mentioning that models with deeper water may contribute to the reduction in RSR and increment of base shear. Further analysis was made to understand the impact of different environmental loads, namely wind, wave, and current, which indirectly includes buoyancy caused by the changes in wave height and tide levels as well as variations in hydrostatic pressure.

Figure 6. Wave height variations as a function of water depth for Platform A.
Figure 7. Wave height variations as a function of water depth for Platform B.

In addition to what has been computed, a brief indication of capturing the relationships of water depth and wave height is as shown in figure 6 for Platform A, which demonstrating the overestimation of wave height at collapse condition by 8%. It is certain that the estimated wave height for WID to happen can be lowered down through the framework assessment proposed in this paper. Similarly, the bar chart presented in figure 7 aims at addressing the overestimation of wave height at collapse, which was found to be approximately 18% larger compared to wave height at WID. For example, the collapse wave height at maximum water depth was initially at 26.88 m and eventually decreased to 21.70 m. It was noticed that for both platforms, the proportions of the governing loads were the same for both the environmental and dead loads, as shown in figures. 8 and 9. Out of 80% of the total environmental load, 92% consists of waves and current load, while wind load contributes to the balance. Despite contributing only 8% of the total environmental load, the wind is also considered one of the important criteria as it affects the upper portion of the structure, such as the topside and the facilities associated with it. Besides that, it also influences the orientation of the jacket platform. Wind load may also contribute forces to the waves, causing them to be stronger and higher at such unpredictable and extreme events. Therefore, these are the key factors that need to be considered in any analysis and design of offshore structures.

Figure 8. Load distributions (in %) of Platform A.

Figure 9. Load distributions (in %) of Platform B.
4. Conclusion
This paper evaluates the factors contributing to wave-in-deck using numerical pushover analysis for fixed jacket structures with assessments made to two platforms operating at shallow water conditions. Results showed that RSR values were dropped for both platforms when WID occurs. On top of that, wind force was found also contributing to the WID event. Safety can be accomplished by managing the risks contributed by these environmental loads. Therefore, this study highlights the importance of considering WID separately to be incorporated in the design values of RSR. The study proposes further considerations to be given not only to the factors considered in this paper but also other influences that may come from the topside loading, equipment damage, etc. However, if the main source of failure comes from WID loading, then these values may still be an informative description to be incorporated in the guideline and design of the structure.

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