Research Article

System Reliability Assessment of Existing Jacket Platforms in Malaysian Waters

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Abstract: Reliability of offshore platforms has become a very important issue in the Malaysian Oil and Gas Industry as, majority of the jacket platforms in Malaysian waters to date, have exceeded their design life. Reliability of a jacket platform can be assessed through reliability index and probability of failure. Conventiona l metocean consideration uses 100 year return period wave height associated with 100 year return period current velocity and wind speed. However, recent study shows that for Malaysian waters, the proposed metocean consideration should be 100 year return period wave height associated with 10 year return period current velocity and wind speed. Hence, this research investigated the effect of different metocean consideration, to system-based reliability of jacket platforms in Malaysian waters. Prior to that, the effect of different metocean consideration to the pushover analysis has also been studied. Besides, the significance of Pile Soil Interaction (PSI), wave direction and platform geometry were analyzed in a sensitivity study. Pushover analysis was performed on three jacket platforms representing three water regions in Malaysia to obtain Reserve Strength Ratio (RSR) as an indicator of the reliability of the jackets. Utilizing sensitivity study parameters mentioned above, seven different case studies were undertaken to study their significance on RSR. The RSR values of each case study were compared and incorporated as resistance model of reliability analysis. Besides, platform specific response model of each jacket has been generated using response surface technique which was later incorporated into the limit state function for reliability analysis. Reliability analysis using First Order Reliability Method (FORM) has been conducted in MATLAB to obtain the reliability index and probability of failure. Results from the reliability analysis were compared to analyze the effect of different metocean consideration. In this study, an updated and detailed methodology of system reliability analysis for offshore jacket platforms is presented. Relationship curves for the safety indices were generated as the outcome of this study. Probability of Failure is found to be inversely functional to RSR. The newly proposed metocean consideration eliminates the conservativeness in currently practiced metocean values. Parameters like metocean considerations and PSI greatly affect the RSR, hence affects Reliability index and Probability of Failure.

Keywords: Metocean, pushover analysis, reserve strength ratio, structural integrity, system reliability

INTRODUCTION

Most of the offshore oil and gas facilities in Malaysia are fixed type platforms fondly known as Jackets. Currently there are over 200 jacket platforms in Malaysian waters (Azman, 2011), all in shallow waters. They are piled to ground and support decks and/or functional structures. Of these, over 60% have been in operation for more than 20 years, 20% of platforms have already exceeded 30 years with several others in the very near future reaching their initial design life of 20-25 years. High oil price coupled with Enhanced Oil Recovery (EOR) technology, demands to extend the life of these platforms resulting in the platforms being subjected to higher loading due to required modifications/upgrading and work-over demands for which the platforms may not have been originally designed for Nichols et al. (2006). In addition, other challenges faced by these platforms are onerous code requirements, increase in environmental metocean loading, presence of shallow gas and seismic/earthquake loading, for which the platforms were not designed. Pushover and reliability analyses are the tools utilized to assess the safety and probability of failure of a jacket structure. Reliability of a jacket platform is governed by its structural system and this system is the combination of series and parallel subsystems.

METOCEAN CONSIDERATION

Wave height, current velocity and wind speed are the dominant factors in design and analysis of offshore jacket platforms. Traditionally, 100 year wave height associated with 100 year current and wind speed, is utilized for design and analysis. This however is not the case according to some researchers as it is very unlikely...
for 100 year wave height, 100 year current and windspeed occur simultaneously. For Malaysian waters, the proposed metocean combination is 100 year wave height associated with 10 year wind and current velocity (Selamat et al., 2013). Authors considered this metocean combination along with the traditional 100 year wave, current, wind combination and also with a metocean combination which exclude wind (Ersdal, 2005).

**PUSHOVER ANALYSIS**

Pushover analysis is widely used in current offshore standards such as API, ISO and DNV to evaluate the ultimate capacity of the platform against the environmental loading (Golashani et al., 2011). Pushover Analysis will provide Reserve Strength Ratio (RSR) value to better assess the platform’s integrity (Narayanan and Kabir, 2009). Knowledge from the analysis can also be used to determine the criticality of components within the structural system and to prioritize the inspection and repair schemes (Rizal, 2011). Pushover analysis which is used to obtain the RSR values of existing aged platforms is crucial because RSR is to be used further in reliability assessment to obtain the likelihood of failure.

In the pushover analysis of an offshore jacket platform, the overall structural response and capacity are dependent on the member behavior in the non-linear range of deformation and also the non-linear interaction of the foundation with the soil. Hence, the pile-soil system is modeled as part of the analysis, which considers non-linear properties of the underlying soil to achieve the most favorable capacity (Asgarian and Lesani, 2009). Thus, this work was undertaken with the aim to study the effect of different metocean considerations to the RSR. It also looks onto the influence of pile soil interaction in pushover analysis.

**SYSTEM RELIABILITY ANALYSIS**

Reliability is defined as ability to achieve desired purpose of platform under operational and extreme conditions throughout its operating life. Reliability of a jacket is measured by its reliability index and probability of failure (Kurian et al., 2012). Structural load-resistance systems are unique; hence the reliability cannot be determined from observation of failures or experimental studies. Under these circumstances, reliability needs to be calculated from predictive models and probabilistic methods.

If a structure exceeds a specific limit, the structure will not be able to perform as required; the specific limit is called a limit state (Choi et al., 2006). The limit state shows the safety margin between resistance and load of the structures. The limit state function, g and probability of failure, $P_f$ is shown in Eq. (1) and (2). Failure of a structural element occurs when the Load model (L) exceeds the Resistance model (R) as shown in Fig. 1 (Stewart, 2001):

$$g = R-L$$

$$P_f = P [g (·) < 0]$$  \tag{2}

$R$ = The resistance of the system

$L$ = The loading of the system

The notation $g (·) < 0$ denotes the failure region while $g (·) = 0$ and $g (·) > 0$ indicates the failure surface and safe region, respectively.

The reliability index or safety index, $\beta$ is defined in Eq. (3):

$$\beta = \frac{\mu_R - \mu_g}{\sqrt{\sigma_R^2 + \sigma_g^2}}$$  \tag{3}
The reliability index represents the distances of the mean margin of safety from the failure surface (Choi et al., 2006). Hence, the larger the value of reliability index, the safer the structure:

**METHODOLOGY**

**Pushover analysis:** Pushover analysis is widely used in calculating the ultimate capacity as well as demonstrating the global instability of jacket platforms (Golashani et al., 2011). Firstly, the gravity load is applied followed by the environmental load onto the structure incrementally while the nodal displacements and element forces are calculated for each load steps and the stiffness matrix is updated. The internal forces and deformation computed at the target displacement levels are estimates of the strength and deformation demands, which need to be compared to available capacities (Krawinkler, 1996). This process will continue until the structure as a whole collapses. Figure 2 below shows the environmental load being applied onto the jacket platform until it collapses. In order to determine the ultimate strength of the platform, it requires information on the updated characteristics of the platform such as platform configuration, foundation characteristics and miscellaneous external forces on the platform (Capanoglu and Coombs, 2009).

Reserve Strength Ratio (RSR) is a measure of structure’s ability to withstand loads in excess of those determined from platform design. This reserve strength can be used to maintain the platform in service beyond their intended service life. Knowledge from the analysis can be used to determine the criticality of components within the structural system and used to prioritize the inspection and repair schemes (Narayanan and Kabir, 2009). RSR is the ratio of collapse base shear to the 100 year return period design base shear as shown in Eq. (4):

$$ RSR = \frac{B_{\text{ultimate}}}{B_{\text{design}}} $$

where, $B_{\text{ultimate}}$ is the ultimate capacity and $B_{\text{design}}$ is design base shear loading on the jacket with respect to 100 year return period metocean loading. The minimum acceptance safety criterion of RSR for a manned structure is 1.50 (Rizal, 2011). Using commercial software, design base shear can be identified when the environmental load factor equals to 1.0, while collapse base shear is the maximum base shear at collapse.

![Jacket before Pushover](image)

![Collapsed Jacket](image)

**Fig. 2:** Pushover analysis by increasing the load factor of environmental loading until the structure collapses

<table>
<thead>
<tr>
<th>Platform 'A'</th>
<th>Platform 'B'</th>
<th>Platform 'C'</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Direction</strong></td>
<td><strong>$H_{\text{max}}$ (m)</strong></td>
<td><strong>$T_{\text{ps}}$ (s)</strong></td>
</tr>
<tr>
<td>N (0°)</td>
<td>11.7</td>
<td>10.9</td>
</tr>
<tr>
<td>NE (45°)</td>
<td>11.7</td>
<td>10.9</td>
</tr>
<tr>
<td>E (90°)</td>
<td>8.7</td>
<td>9.8</td>
</tr>
<tr>
<td>SE (135°)</td>
<td>6.3</td>
<td>9.7</td>
</tr>
<tr>
<td>S (180°)</td>
<td>6.3</td>
<td>9.7</td>
</tr>
<tr>
<td>SW (225°)</td>
<td>8.7</td>
<td>9.8</td>
</tr>
<tr>
<td>W (270°)</td>
<td>10.2</td>
<td>10.3</td>
</tr>
<tr>
<td>NW (315°)</td>
<td>11.7</td>
<td>10.9</td>
</tr>
</tbody>
</table>

Table 1: Wave properties for platform 'A', 'B' and 'C'

100-Year return period wave properties

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Progressive collapse analysis. The metocean data is shown in Table 1 to 3.

Table 2: 100-year and 10-year wind and current properties for platform 'A' and 'B'

<table>
<thead>
<tr>
<th>Wind speed (m/s)</th>
<th>Current velocity (m/s)</th>
<th>Wind speed (m/s)</th>
<th>Current velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-hour mean</td>
<td>1.0*D</td>
<td>1.0*D</td>
<td>1.0*D</td>
</tr>
<tr>
<td>10-min mean</td>
<td>0.5*D</td>
<td>0.5*D</td>
<td>0.5*D</td>
</tr>
<tr>
<td>3-sec gust</td>
<td>0.01*D</td>
<td>0.01*D</td>
<td>0.01*D</td>
</tr>
</tbody>
</table>

Table 3: 100-year and 10-year wind and current properties for platform 'C'

<table>
<thead>
<tr>
<th>Wind speed (m/s)</th>
<th>Current velocity (m/s)</th>
<th>Wind speed (m/s)</th>
<th>Current velocity (m/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1-hour mean</td>
<td>1.0*D</td>
<td>1.0*D</td>
<td>1.0*D</td>
</tr>
<tr>
<td>10-min mean</td>
<td>0.5*D</td>
<td>0.5*D</td>
<td>0.5*D</td>
</tr>
<tr>
<td>3-sec gust</td>
<td>0.01*D</td>
<td>0.01*D</td>
<td>0.01*D</td>
</tr>
</tbody>
</table>

Fig. 3: The jacket model of platform 'A', 'B' and 'C' from left to right, respectively

Pushover analysis consists of three major steps which are data preparation, structural modelling and progressive collapse analysis. The metocean data is incorporated into the program to generate environmental loads onto the structure. Three platforms were used for the analysis namely Platform 'A', 'B' and 'C' representing three different water regions in Malaysia, namely Sarawak (SKO), Sabah (SBO) and Peninsula (PMO). The metocean data of those platforms is shown in Table 1 to 3.

Directional wave properties were incorporated into the model in eight different directions, while current and wind were incorporated as similar value for all eight different directions due to lack of direction-specific metocean data for platform 'A' and 'B'. Pushover analysis was conducted on jacket platforms 'A', 'B' and 'C' as shown in Fig. 3. Platforms 'A' and 'C' are four-legged while platform 'B' is six-legged. There were seven cases studied namely Case A, Case B, Case
The load model and resistance model equations for Case Ware shown in Eq. (5) and Eq. (9), respectively. Since wind effect is ignored for Case W, the variables in the load model equation only consist of wave height and current. Meanwhile, wave height, current and wind were used as variables as shown in Eq. (6-8) and Eq. (10-12):

Load model:

- **Case W:**
  \[ L = \alpha \cdot C_1 \cdot (H_{100} + C_2 \cdot U_{100})^{C_3} \]  
  \[ L = \alpha \cdot (C_1 \cdot H_{100}^2 + C_2 \cdot H_{100} + C_3 \cdot U_{100}^2 + C_4 \cdot U_{100} + C_5 \cdot W_{100} + C_7) \]  
  \[ L = \alpha \cdot (C_1 \cdot H_{100}^2 + C_2 \cdot H_{100} + C_3 \cdot U_{100}^2 + C_4 \cdot U_{100} + C_5 \cdot W_{100} + C_7) \]  
  \[ L = \alpha \cdot (C_1 \cdot H_{100}^2 + C_2 \cdot H_{100} + C_3 \cdot U_{100}^2 + C_4 \cdot U_{100} + C_5 \cdot W_{100} + C_7) \]  
  \[ L = \alpha \cdot (C_1 \cdot H_{100}^2 + C_2 \cdot H_{100} + C_3 \cdot U_{100}^2 + C_4 \cdot U_{100} + C_5 \cdot W_{100} + C_7) \]

where,
- \( \alpha \) = The uncertainty factor for load model
- \( H_{100} \) = The 100 year wave height
- \( U_{100} \) = The 100 year current velocity
- \( C_1, C_2, C_3, C_4, C_5, C_6 \) and \( C_7 \) = Load coefficients that must be curve-fitted to calculate load model for specific jacket (Ersdal, 2005)

- **Case X:**
  \[ L = \alpha \cdot (C_1 \cdot H_{100}^2 + C_2 \cdot H_{100} + C_3 \cdot U_{100}^2 + C_4 \cdot U_{100} + C_5 \cdot W_{100} + C_7) \]

- **Case Y:**
  \[ L = \alpha \cdot (C_1 \cdot H_{100}^2 + C_2 \cdot H_{100} + C_3 \cdot U_{100}^2 + C_4 \cdot U_{100} + C_5 \cdot W_{100} + C_7) \]

- **Case Z:**
  \[ L = \alpha \cdot (C_1 \cdot H_{100}^2 + C_2 \cdot H_{100} + C_3 \cdot U_{100}^2 + C_4 \cdot U_{100} + C_5 \cdot W_{100} + C_7) \]

Resistance model: Resistance for system reliability is modelled as an ultimate capacity of the structure. The expected value of ultimate capacity is assumed to be equal to the loading multiplied with Reserve Strength Ratio (RSR) and accounted for resistance model uncertainty.
Case W:

The resistance for case W is approximated by the following equation:

\[ R = \beta \cdot RSR \cdot (C_1 \cdot H_{100} + C_2 \cdot U_{100} + C_3 \cdot U_{10})^3 \]

(9)

where, \( \beta \) is the uncertainty factor for resistance model, \( RSR \) is Reserve Strength Ratio, obtained from pushover analysis on the platform using associated metocean loading, \( H_{100} \) is the 100 year wave height, \( U_{100} \) is the 100 year current velocity, \( C_1, C_2, \) and \( C_3 \) are load coefficients which were curve-fitted to calculate load model for specific jacket (Ersdal, 2005).

Case X:

\[ R = \beta \cdot RSR \cdot (C_1 \cdot H_{100} + C_2 \cdot H_{100} + C_3 \cdot U_{100}^2 + C_4 \cdot U_{10} + C_5 \cdot W_{10}^2 + C_6 \cdot W_{10} + C_7) \]

(10)

Case Y:

\[ R = \beta \cdot RSR \cdot (C_1 \cdot H_{100} + C_2 \cdot H_{10} + C_3 \cdot U_{10}^2 + C_4 \cdot U_{10} + C_5 \cdot W_{10}^2 + C_6 \cdot W_{10} + C_7) \]

(11)

Case Z:

\[ R = \beta \cdot RSR \cdot (C_1 \cdot H_{100} + C_2 \cdot H_{100} + C_3 \cdot U_{10}^2 + C_4 \cdot U_{10} + C_5 \cdot W_{10}^2 + C_6 \cdot W_{10} + C_7) \]

(12)

where,

\( \beta \) = The uncertainty factor for resistance model

\( RSR \) = Reserve Strength Ratio, obtained from pushover analysis on the platform using associated metocean loading

\( H_{100} \) = The 100 year wave height

\( U_{100} \) = The 100 year current velocity

\( U_{10} \) = The 10 year current velocity

\( W_{100} \) = The 100 year wind speed

\( W_{10} \) = The 10 year wind speed; 1 min mean for Case Y and 3 sec gust for Case Z.

\( C_1, C_2, C_3, C_4, C_5, C_6 \) and \( C_7 \) are load coefficients that were curve-fitted to calculate load model for specific jacket (Cossa, 2012).

For curve fitting, static analysis for each platform was conducted for all 4 cases to generate the responses (Base Shear) based on varying wave height as shown in Fig. 4 to 6. The Base Shear generated at all 8 directions of the platform for that particular loading direction was inputted for the curve fitting process. The data was regressed at 95% confidence level and the load coefficients were generated using least mean square method. The coefficient of determination, \( R^2 \) is above 0.95 for both platform ‘A’ and ‘C’, while \( R^2 \) is above 0.90 for platform ‘B’. Due to the nature of geometry of six-legged platform ‘B’, the Base Shear generated was not that consistent in all 8 directions, resulting in lower \( R^2 \). The generated load coefficients are shown in Table 6 to 8 for platform ‘A’, ‘B’ and ‘C’ for all 4 cases.

Limit state equation: A failure function for the ultimate collapse of structure can be modelled using the following equation:

\[ g = R - L \]

(13)
Probability of failure is given by the probability of that failure function is equal or less than 0. The reliability analysis was conducted using First Order Reliability Method (FORM). The COV of load uncertainty is recommended at 0.15 while COV of resistance uncertainty is recommended at 0.10 (Ersdal, 2005). In this study, Reliability Analysis was conducted on all 8 directions of the platforms instead of only the most critical direction of the platform.

RESULTS AND DISCUSSION

Pushover analysis: Figure 7 to 9 show the pushover analysis results for platform 'A', 'B' and 'C' respectively. Case A and Case B were compared to each other to study the effect of Pile Soil Interaction on the value of RSR; by including PSI consideration in the pushover analysis for Case A and excluding PSI for Case B. Besides the effect of PSI, Case B has the purpose of studying the geometry effect of the jacket platform by excluding the PSI effect in the analysis and using the same maximum metocean loading on all 8 directions. Case C and Case D looked into the effect of omni-direction metocean loading which is different at each direction with Case C excluding PSI consideration. Cases E and F studied the proposed metocean combination which was 100 year wave associated with 10 year wind and current compared with Case D; to observe the effect in resulting RSR. Case G was similar to case D but excludes the wind effect in the pushover analysis.

It was observed that metocean loading affects the RSR greatly as cases which include variation in metocean for example Case C, D, E, F and G for both jackets show variation in the RSR values. Meanwhile, Case A and Case B which use maximum metocean loading for all directions do not display much variation in terms of RSR for all 8 different directions. It was observed that PSI is important in pushover analysis as it greatly affects the RSR value too. RSR from Case B and Case C was considerably higher than Case A and Case D, respectively, under similar circumstances with the only difference being the consideration of PSI.
From the results, it was observed that Case E and Case F which consider metocean combination of 100 year wave associated with 10 year current and wind produces RSR which is generally higher than Case D which considers 100 year return period for wave, current and wind. For Case G, metocean loading of only wave and current was used for the pushover analysis and the RSR produced was observed to be much higher than case D as well. This is especially obvious for jacket 'B' since the adopted 100 year windspeed was 40 m/s which contributed significantly to the loading onto the platform. Although the RSR values of case D was not the most critical compared to Case A, B and C, it is the closest estimate to the real existing platform’s strength considering the conventional metocean. Case E, Case F and Case G were compared to Case D as only the metocean consideration was different while other conditions were the same.

The RSR values were incorporated into the reliability analysis as such; RSR from Case D was used in reliability analysis Case X, RSR from Case E into Case Y, RSR from Case F into Case Z and RSR from Case G into Case W, respectively.

Reliability analysis: Table 9 shows the result of Reliability Analysis for three jacket platforms studied for Case W, Case X, Case Y and Case Z. The information from the table includes the Probability of Failure (PoF) at each direction of the jacket platforms, the corresponding Reliability Index (RI) and RSR. The category of the four cases studied is as explained in Table 5.
Meanwhile, the higher value of Probability of Failure means that the likelihood of a platform failure is higher, hence the lower the value of Probability of Failure, the safer the platform is. Reliability Index represents the distance of the mean margin of safety from the failure surface and is usually presented alongside with Probability of Failure as a safety index, in which the higher the value of Reliability Index, the safer the platform is. The relationship of these three results can be observed in Fig. 10 to 13. The results plotted in Fig. 10 to 13 is combination of all three platforms with all the directional values. The higher the value of RSR, it was observed that the corresponding Probability of Failure is lower for all four cases corresponding to higher Reliability Index. This applies to all four cases studied.

For simplicity of discussion, authors discuss the reliability analysis in terms of Probability of Failure hereafter. Case W and Case X were compared to each other to study the effect of wind on the value of Probability of Failure. Case Y and Case Z were looked into the effect of newly proposed metocean condition against Case X with the only difference between Case Y and Case Z is in the frequency of wind used. It was observed that the Probability of Failure of Case W is generally lower than Probability of Failure of Case X. This shows that the wind loading greatly affects the difference of Probability of Failure between Case W and Case X, especially for Platform ‘B’ because the wind speed imposed on platform ‘B’ is much higher compared to the other two platforms as shown in Table 2 and 3. Hence, it was not surprising to observe the drastic increase in Probability of Failure for platform ‘B’ when wind is included.

From the results, it is noticeable that Case Y and Case Z generally have Probability of Failure lower than Case X as Case Y and Case Z utilizes different metocean combination from Case X which is the current industry practice. Results also show that Probability of Failure in Case Z is slightly higher as compared to Case Y due to different frequency of wind used which are three second gust for Case Z and one minute mean for Case Y. This difference in result implicates that even though the return period of the metocean is the same, different types of wind frequency greatly influence the reliability indices of jacket platforms.

## CONCLUSION

By performing pushover and reliability analyses, the safety indices of jacket platforms can be determined. These analyses are necessary to identify the integrity and fit-for-purpose of any aging jacket platforms for the extension of life. In this study, comparison between conventional metocean values and newly proposed metocean values were conducted. Sensitivity study to assess the significance of...
parametric values was done prior to reliability analysis. Response Surface method was used to generate platform specific load and resistance model to be used in the reliability analysis. Curve fitting method was used to identify the response surface load coefficients in the analysis. FORM in MATLAB was adopted as the tool in assessing the limit state function in the reliability analysis. Relationship curves for the safety indices were generated as the outcome of this study. The following conclusions were drawn from the results of this study:

- Pushover analysis using the newly proposed metocean combination of 100 year wave height associated with 10 year of current and 10 year of wind speed generally results in smaller RSR than currently practiced metocean combination values.
- Metocean combinations, directions and pile soil interaction greatly affect the RSR and hence affect Reliability index and Probability of Failure.
- The newly proposed metocean consideration in both cases of Y and Z with a difference of wind speed frequency of one minute mean and three second gust, respectively, generally result in lower Probability of Failure than Case X which utilized conventional metocean consideration.
- Probability of Failure is inversely functional to RSR. The lower the value of Probability of Failure or the higher the value of the RSR, the safer or more reliable the platforms are.
- From relationship curves, smaller RSR values produce abruptly changing Probability of Failure and vice versa.

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