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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. Conventional 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

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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):

$$g = R - L \quad (1)$$

$$P_f = P\,[g(\cdot) < 0] \quad (2)$$

R = The resistance of the system
L = The loading of the system

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

The reliability index or safety index, β is defined in Eq. (3):

$$\beta = \frac{\mu_R - \mu_S}{\sqrt{\sigma_R^2 + \sigma_S^2}} \quad (3)$$

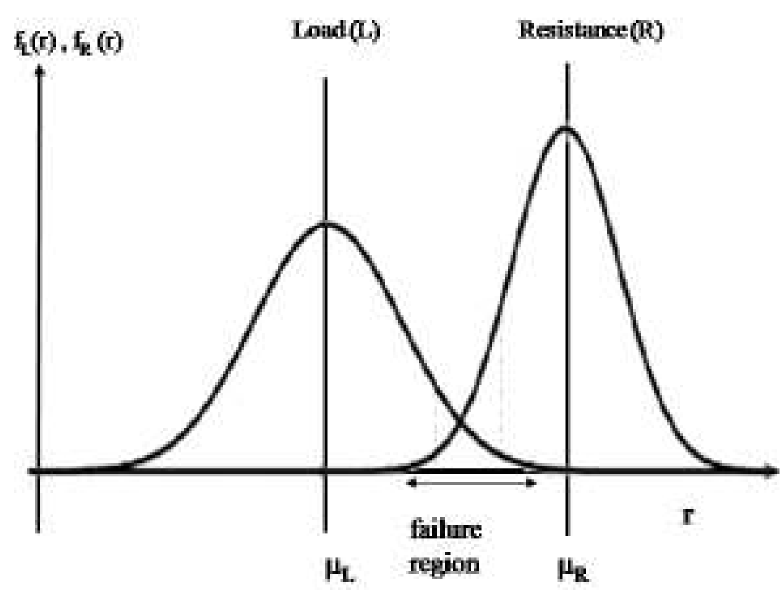

Fig. 1: Definition of probability of failure

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):

$$RSR = \frac{BS_{ultimate}}{BS_{design}} \tag{4}$$

where, $BS_{ultimate}$ is the ultimate capacity and BS_{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.

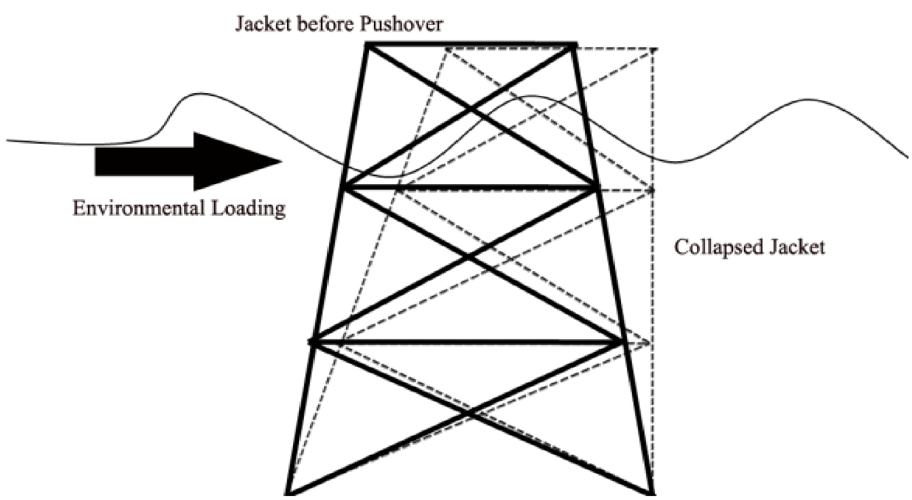

Fig. 2: Pushover analysis by increasing the load factor of environmental loading until the structure collapses

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

100-Year return period wave properties								
Platform 'A'			Platform 'B'			Platform 'C'		
Direction	H_{max} (m)	T_{ass}(s)	Direction	H_{max} (m)	T_{ass}(s)	Direction	H_{max} (m)	T_{ass}(s)
N (0°)	11.7	10.9	N (0°)	7.7	8.6	N (0°)	8.7	8.6
NE (45°)	11.7	10.9	NE (61°)	4.0	6.3	NE (45°)	10.9	9.5
E (90°)	8.7	9.8	E (90°)	4.0	6.3	E (90°)	6.5	7.2
SE (135°)	6.3	9.7	SE (118°)	2.3	4.7	SE (135°)	6.5	7.2
S (180°)	6.3	9.7	S (180°)	2.3	4.7	S (180°)	6.5	7.2
SW (225°)	8.7	9.8	SW (241°)	7.7	8.6	SW (225°)	7	7.7
W (270°)	10.2	10.3	W (270°)	7.7	8.6	W (270°)	7	7.7
NW (315°)	11.7	10.9	NW (298°)	7.7	8.6	NW (315°)	8.7	8.6

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

100-Year return period wind and current for 'A'					100-Year return period wind and current for 'B'				
Wind speed (m/s)		Current velocity (m/s)			Wind speed (m/s)		Current velocity (m/s)		
1-hour mean	20				1-hour mean	32	Surface	1.0*D	0.94
10-min mean	22	Surface	1.0*D	1.20	1-min mean	40	Mid depth	0.5*D	0.86
1-min mean	24	Mid depth	0.5*D	0.95	3-sec gust	50	Near bottom	0.1*D	0.68
3-sec gust	26	Near Seabed	0.01*D	0.55			Near Seabed	0.01*D	0.44
10-Year return period wind and current for 'A'					10-Year return period wind and current for 'B'				
Wind speed (m/s)		Current velocity (m/s)			Wind speed (m/s)		Current velocity		
1-hour mean	17				1-hour mean	19	Surface	1.0*D	0.78
10-min mean	18	Surface	1.0*D	1.05	1-min mean	24	Mid depth	0.5*D	0.70
1-min mean	20	Mid depth	0.5*D	0.83	3-sec gust	29	Near bottom	0.1*D	0.56
3-sec gust	22	Near Seabed	0.01*D	0.50			Near Seabed	0.01*D	0.37

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

100-Year return period wind and current											
Wind speed (m/s)		Current velocity (m/s)		0	45	90	135	180	225	270	315
1-hour mean	23.0	Surface	1.0*D	0.82	1.29	1.29	0.86	1.47	1.47	1.47	0.82
10-min mean	25.0	Mid depth	0.5*D	0.65	1.02	1.02	0.68	1.17	1.17	1.17	0.65
1-min mean	29.0	Near bottom	0.1*D	0.38	0.60	0.60	0.40	0.68	0.68	0.68	0.38
3-sec gust	35.0	Near Seabed	0.01*D	0.18	0.28	0.28	0.19	0.32	0.32	0.32	0.18
10-Year return period wind and current											
Wind speed (m/s)		Current velocity (m/s)		0	45	90	135	180	225	270	315
1-hour mean	20.0	Surface	1.0*D	0.71	1.17	1.17	0.74	1.14	1.14	1.14	0.71
10-min mean	22.0	Mid depth	0.5*D	0.56	0.93	0.93	0.59	0.90	0.90	0.90	0.56
1-min mean	25.0	Near bottom	0.1*D	0.33	0.54	0.54	0.34	0.53	0.53	0.53	0.33
3-sec gust	30.0	Near Seabed	0.01*D	0.15	0.25	0.25	0.16	0.25	0.25	0.25	0.15

(a) (b) (c)

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

Table 4: Pushover analysis sensitivity study

	Pushover analysis	Case						
	Conditions	A	B	C	D	E	F	G
1	Pile Soil Interaction (PSI)	X			X	X	X	X
2	Omni-direction Metocean	X	X					
3	Multi-direction Metocean			X	X	X	X	X
4	100-10-10 Metocean					X	X	
5	Wind : 1 min mean	X	X	X	X	X		
6	Wind : 3 second gust						X	
7	Excludes wind effect							X

Table 5: Different cases for system reliability

Case	Remarks
W	100 year wave and 100 year current
X	100 year wave, 100 year current and 100 year wind (1 minute mean)
Y	100 year wave, 10 year current and 10 year wind (1 minute mean)
Z	100 year wave, 10 year current and 10 year wind (3 second gust)

C, Case D, Case E, Case F and Case G. The seven different cases with their selection of scenarios are shown in Table 4.

Pushover analysis was carried out using commercial software separately for eight selected loading directions namely; N (0°), NE (45°), E (90°), SE (135°), S (180°), SW (225°), W (270°) and NW (315°) for jacket 'A', jacket 'C' while jacket 'B' was assessed at N (0°), NE (61°), E (90°), SE (118°), S (180°), SW (241°), W (270°) and NW (298°). The slight difference in the direction was mainly due to the difference in the platform geometry. RSR values from Case D, Case E, Case F and Case G were used as resistance model in the limit state function in the reliability analysis.

Reliability analysis:

Response surface: Wave, current and wind loads are the major loads experienced by jacket platforms throughout its operation life. Probability of failure is ascertained for the assessment of jacket platform for life extension purpose. Existing jacket platform after surviving severe loading condition from some storm events are considered safe for such type of storm if they ever occur again. Authors studied the effect of different metocean values combinations on the reliability analysis of jacket platforms in Malaysian waters as shown in Table 5.

Response Surface method is used to obtain a parametric representation of environmental load onto the platform (Petrauskas *et al*., 1994). The aim was to generate the load model equation which was incorporated in the reliability analysis. Different load model equations were identified for each case shown in Table 5. The load coefficients in the load model equations are different due to different metocean consideration. Also, the load coefficients are parameters that are structural dependant and platform specific. Hence response surface was utilized on all three platforms.

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:**

$$L = \alpha \cdot C_1 \cdot (H_{100} + C_2 \cdot U_{100})^{C_3} \quad (5)$$

where,

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

- **Case X:**

$$L = \alpha \cdot (C_1 \cdot H_{100}{}^2 + C_2 \cdot H_{100} + C_3 \cdot U_{100}{}^2 + C_4 \cdot U_{100} + C_5 \cdot W_{100}{}^2 + C_6 \cdot W_{100} + C_7) \quad (6)$$

- **Case Y:**

$$L = \alpha \cdot (C_1 \cdot H_{100}{}^2 + C_2 \cdot H_{100} + C_3 \cdot U_{10}{}^2 + C_4 \cdot U_{10} + C_5 \cdot W_{10}{}^2 + C_6 \cdot W_{10} + C_7) \quad (7)$$

- **Case Z:**

$$L = \alpha \cdot (C_1 \cdot H_{100}{}^2 + C_2 \cdot H_{100} + C_3 \cdot U_{10}{}^2 + C_4 \cdot U_{10} + C_5 \cdot W_{10}{}^2 + C_6 \cdot W_{10} + C_7) \quad (8)$$

where,

- α = The uncertainty factor for load model
- 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 must be curve-fitted to calculate load model for specific jacket (Cossa, 2012).

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.

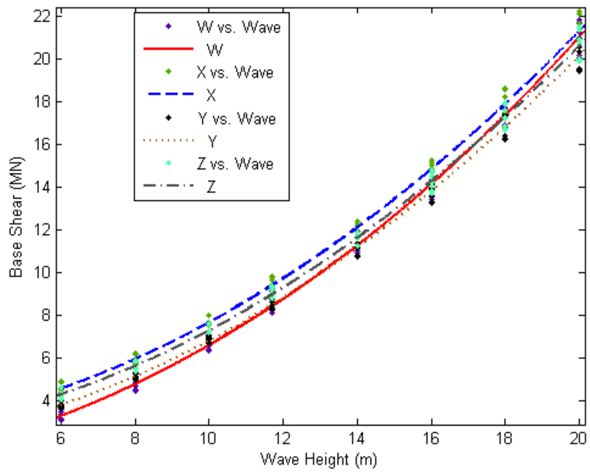

Fig. 4: Curve fit for case W, X, Y and Z platform 'A'

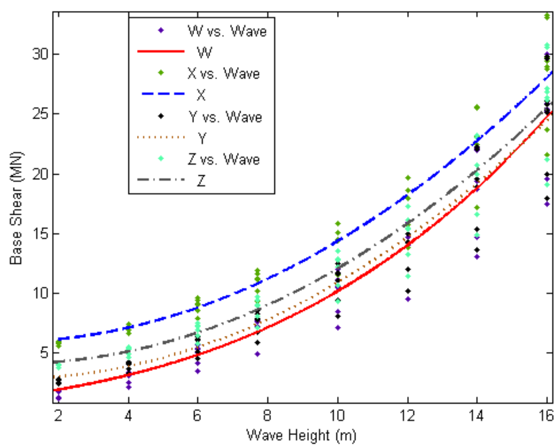

Fig. 5: Curve fit for case W, X, Y and Z platform 'B'

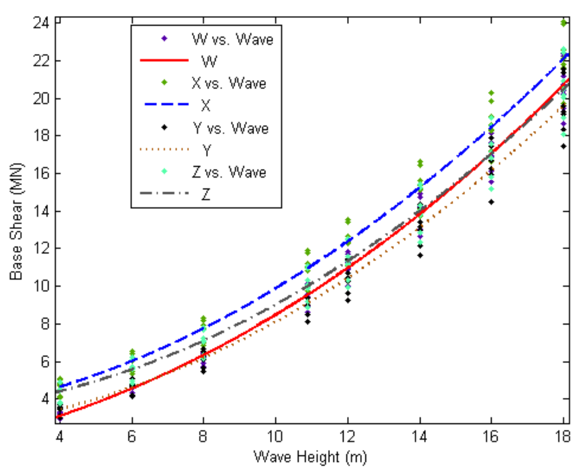

Fig. 6: Curve fit for case W, X, Y and Z platform 'C'

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

$$R = \beta \cdot \mathrm{RSR} \cdot C_1 \cdot (H_{100} + C_2 \cdot U_{100})^{C_3} \quad (9)$$

where, β 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:**

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

- **Case Y:**

$$R = \beta \cdot \mathrm{RSR} \cdot (C_1 \cdot {H_{100}}^2 + C_2 \cdot H_{100} + C_3 \cdot {U_{10}}^2 + C_4 \cdot U_{10} + C_5 \cdot {W_{10}}^2 + C_6 \cdot W_{10} +) \quad (11)$$

- **Case Z:**

$$R = \beta \cdot \mathrm{RSR} \cdot (C_1 \cdot {H_{100}}^2 + C_2 \cdot H_{100} + C_3 \cdot {U_{10}}^2 + C_4 \cdot U_{10} + C_5 \cdot {W_{10}}^2 + C_6 \cdot W_{10} + C_7) \quad (12)$$

where,

β = 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 for 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:

$$g = R - L \quad (13)$$

Table 6: The load coefficients for platform 'A'

Load Coeff.	W	X	Y	Z
C_1	0.01251	0.04232	0.04192	0.04188
C_2	4.359	0.09672	0.08061	0.07821
C_3	2.301	2.298	0.2373	0.5075
C_4	-	0.9034	0.4435	0.5523
C_5	-	-0.04453	-0.02386	-0.03047
C_6	-	0.9760	0.5088	0.7178
C_7	-	0.2843	0.4315	0.1217

Table 7: The load coefficients for platform 'B'

Load Coeff.	W	X	Y	Z
C_1	8.976e-005	0.08996	0.0914	0.09048
C_2	13.17	-0.05428	-0.1135	-0.1100
C_3	3.744	-1.301	-1.471	0.7819
C_4	-	9.444	2.545	-0.4716
C_5	-	-0.01863	-0.008581	-0.02307
C_6	-	0.6941	0.2791	0.7959
C_7	-	0.2226	0.05128	0.3432

Table 8: The load coefficients for platform 'C'

Load Coeff.	W	X	Y	Z
C_1	0.01065	0.04664	0.04726	0.0474
C_2	4.928	0.2196	0.1152	0.1060
C_3	2.346	1.032	0.8548	0.4228
C_4	-	2.415	0.2537	-0.4468
C_5	-	-0.0267	-0.01908	-0.009477
C_6	-	0.6650	0.4927	0.3866
C_7	-	0.4125	0.4433	0.1253

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.

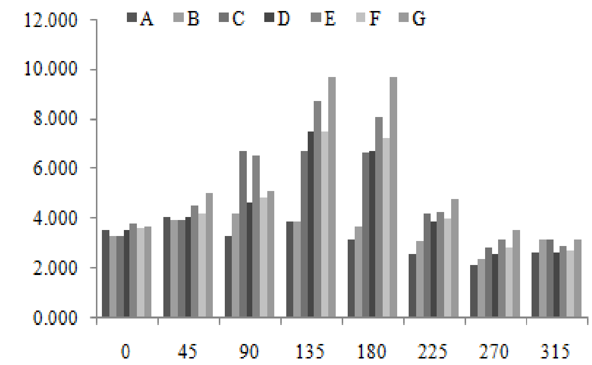

Fig. 7: The RSR results for Jacket 'A'

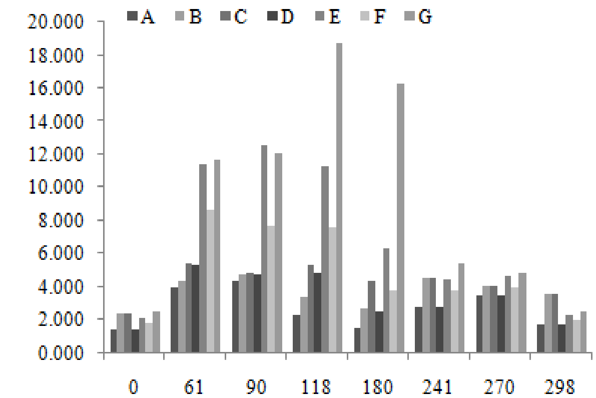

Fig. 8: The RSR results for Jacket 'B'

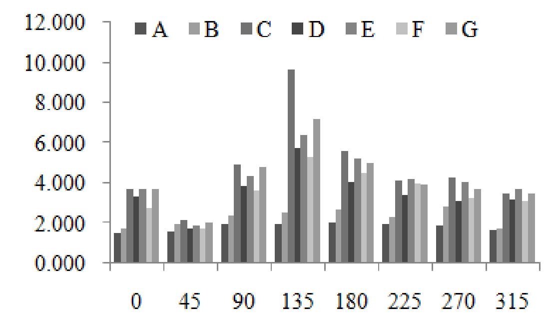

Fig. 9: The RSR results for Jacket 'C'

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.

Table 9: The result of reliability analysis result namely: Probability of failure (PoF), Reliability Index (RI) and RSR of Platform 'A', 'B' and 'C' for Case W, Case X, Case Y and Case Z

Platform 'A'				Platform 'B'				Platform 'C'			
Case W				Case W				Case W			
Dir	PoF	RI	RSR	Dir.	PoF	RI	RSR	Dir.	PoF	RI	RSR
0	2.16E-12	6.926	3.699	0	2.45E-07	5.031	2.441	0	5.25E-13	7.124	3.686
45	2.72E-15	7.816	5.060	61	6.12E-20	9.067	11.650	45	1.44E-05	4.183	2.010
90	2.44E-15	7.831	5.083	90	4.35E-20	9.104	12.101	90	1.02E-14	7.648	4.769
135	2.69E-19	8.904	9.708	118	1.92E-21	9.437	18.761	135	4.96E-18	8.575	7.168
180	2.76E-19	8.901	9.686	180	4.51E-21	9.347	16.296	180	4.33E-15	7.757	5.030
225	7.33E-15	7.690	4.800	241	2.11E-15	7.847	5.391	225	5.44E-13	7.119	3.962
270	5.49E-12	6.793	3.553	270	1.82E-14	7.573	4.830	270	2.06E-12	6.933	3.739
315	1.08E-10	6.350	3.149	298	1.49E-07	5.125	2.489	315	1.91E-12	6.944	3.491
Case X				Case X				Case X			
Dir.	PoF	RI	RSR	Dir.	PoF	RI	RSR	Dir.	PoF	RI	RSR
0	1.69E-12	6.961	3.533	0	2.81E-03	2.769	1.370	0	1.58E-06	4.661	3.350
45	5.80E-14	7.421	4.060	61	5.55E-16	8.011	5.273	45	3.18E-05	3.999	1.750
90	3.00E-15	7.804	4.673	90	5.88E-15	7.718	4.659	90	2.78E-11	6.555	3.840
135	1.29E-18	8.728	7.455	118	8.77E-15	7.667	4.846	135	2.80E-12	6.889	5.731
180	5.65E-18	8.560	6.693	180	1.34E-07	5.145	2.420	180	1.25E-12	7.003	4.082
225	3.05E-13	7.198	3.840	241	7.13E-10	6.052	2.751	225	1.07E-08	5.600	3.399
270	5.79E-09	5.706	2.579	270	2.78E-12	6.890	3.425	270	4.40E-08	5.350	3.130
315	2.09E-09	5.877	2.670	298	1.48E-04	3.618	1.626	315	2.48E-06	4.567	3.220
Case Y				Case Y				Case Y			
Dir.	PoF	RI	RSR	Dir.	PoF	RI	RSR	Dir.	PoF	RI	RSR
0	3.13E-13	7.195	3.807	0	8.78E-07	4.780	2.082	0	1.03E-07	5.193	3.710
45	5.11E-15	7.738	4.540	61	1.78E-20	9.201	11.351	45	5.83E-06	4.384	1.900
90	5.80E-18	8.557	6.489	90	8.05E-21	9.286	12.581	90	8.51E-13	7.057	4.400
135	1.67E-19	8.957	8.717	118	4.80E-20	9.094	11.321	135	6.11E-16	8.005	6.401
180	3.94E-19	8.862	8.082	180	5.55E-17	8.276	6.260	180	1.18E-14	7.630	5.246
225	3.51E-14	7.488	4.260	241	1.05E-14	7.644	4.385	225	1.22E-09	5.965	4.213
270	3.61E-11	6.516	3.185	270	3.83E-15	7.773	4.588	270	2.57E-09	5.843	4.038
315	3.63E-10	6.160	2.880	298	1.21E-07	5.163	2.270	315	1.09E-07	5.183	3.696
Case Z				Case Z				Case Z			
Dir.	PoF	RI	RSR	Dir.	PoF	RI	RSR	Dir.	PoF	RI	RSR
0	1.06E-12	7.027	3.606	0	4.03E-05	3.943	1.729	0	1.08E-06	4.738	2.755
45	2.43E-14	7.536	4.220	61	3.55E-19	8.873	8.614	45	3.39E-05	3.984	1.760
90	1.55E-15	7.889	4.831	90	1.40E-18	8.719	7.670	90	2.04E-07	5.066	3.619
135	1.14E-18	8.743	7.516	118	5.35E-18	8.566	7.522	135	5.65E-08	5.305	5.301
180	1.87E-18	8.686	7.233	180	1.73E-12	6.958	3.774	180	8.01E-09	5.650	4.537
225	1.28E-13	7.316	3.990	241	4.43E-13	7.147	3.707	225	1.71E-06	4.644	3.980
270	5.57E-10	6.092	2.837	270	8.65E-14	7.368	3.970	270	1.14E-05	4.235	3.271
315	1.42E-09	5.940	2.715	298	2.28E-06	4.584	1.983	315	3.64E-05	3.967	3.110

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.

It was observed that Probability of Failure is inversely related to the RSR. The larger the value of RSR means the safer the jacket platform as higher RSR value means the platforms having higher reserve capacity against the imposing environmental loadings.

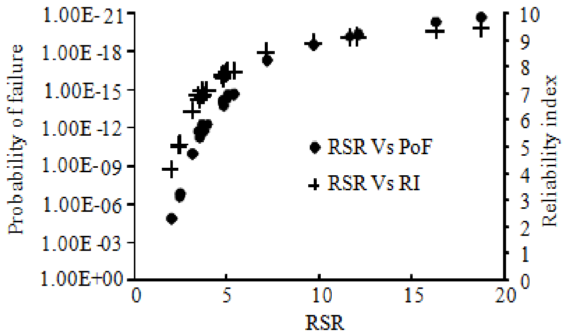

Fig. 10: Probability of failure vs. RSR and reliability index vs. RSR for case W

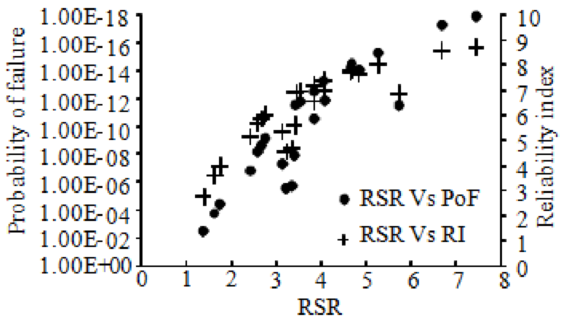

Fig. 11: Probability of failure vs. RSR and reliability index vs. RSR for case X

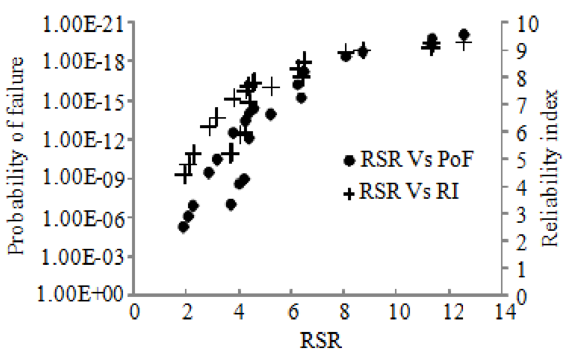

Fig. 12: Probability of failure vs. RSR and reliability index vs. RSR for case Y

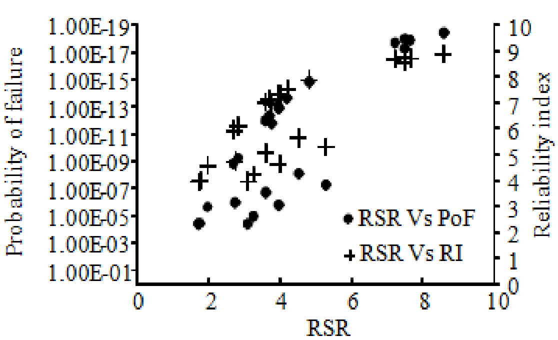

Fig. 13: Probability of failure vs. RSR and reliability index vs. RSR for case Z

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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