Reliability of Jacket Platforms in Malaysian Waters

Sensitivity Study using Pushover Analysis

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***Abstract*—Issues regard to continued usage of aging jacket platforms and Enhanced Oil Recovery (EOR) affecting the aged fixed jacket platforms owned by PETRONAS in Malaysian waters was studied. Pile buckling together with lateral soil failure and lengthy/ monotonous reliability analysis were identified as the core research issues related to the problem statement. SACS software was used on existing jacket platform structural model to carry out pushover analyses. Reserve Strength Ratio (RSR) was obtained through different combinations of dead, live, and storm loads. It was found that live load combinations had insignificance on the RSR value compared to variation in storm directions. RSR values from directional loads and resistance are very much volatile and significant. The response of the pile foundation to the environmental load is strongly affected by pile soil interaction. Since the development of p-y curve represents the pile foundation and soil structure interaction, it was used to model the soil resistance to the pile movements and the results obtained were analyzed. Collapse analysis with PSI yields lower RSR compared to an analysis without PSI. Inclusion of PSI (pile soil interaction) increased the RSR value in the range of 5.6% to 50.1%. A trend called slender column and truss system effects were introduced for the pushover analysis with and without PSI, respectively. Sensitivity study was in agreement with failure mechanisms experienced in the pushover analysis.**

***Index Terms* — Reliability, Jacket Platforms, RSR, p-y curve, pile-soil interaction.**

I. INTRODUCTION

Malaysian oil and gas industry blossomed in mid 70's by setting up of the Petroleum Development Act followed by establishment of Petroleum Nasional Berhad (PETRONAS); the national oil and gas company, in 1974. Most of the offshore oil and gas resources are found in three states of Malaysia, namely Terengganu, Sabah and Sarawak. Petronas Carigali Sdn Bhd (PCSB)-the exploration and production (E&P) company of PETRONAS currently operating over 200 offshore facilities in Malaysian waters [1]. Most of these facilities are fixed type of platforms. 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 (20-25 years) [2]. Almost all early offshore rigs were fixed platforms or fondly known as Jackets, mostly in shallow waters. They are piled to ground and supports decks and/or functional structures.

Profit Sharing Contract (PSC) was the term used for the initiative between global players and PETRONAS for the development of the facilities. Under the contract, PETRONAS owns the asset, but the PSC partners will develop and manage the field and its facilities throughout the contract duration. Profit will be shared between the parties with a predetermined ratio. Contract period, mostly around 20 to 25 years. After the completion of the contract, the platform assets will be returned to PETRONAS. The Asset condition during the handing over is aged, with high wear and tear yet acceptably maintained

II. PROBLEM STATEMENT

For Enhanced Oil Recovery (EOR), there is an increasing demand to extend the life of these platforms. This results 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 [2]. An existing platform should undergo assessment process if one or more of the following conditions exist; (a) Addition of personal, (b) Increased loading on structure, (c) Damage found during inspection [3]. In addition, other challenges faced by these platforms, e.g. onerous code requirements, increase in environmental met-ocean loading, presence of shallow gas and seismic/ earthquake loading; again for which the platform was not designed for initially [2].

For these cases, the engineers are faced with tasks where little guidance is found in design standards and the analysis required are often based on advanced techniques and methodology that is seldom used in design of new structures. Design standards are based on theories, methods and experience for structures in a given design life (e.g. fatigue design and corrosion protection design). When the design life is extended, sound methods for ensuring the structures are still sufficiently safe is needed. Such methods will normally be "condition based design", where inspection, maintenance and repairs are included in the assessment in an integrated way [4].

III. LITERATURE

Reliability is the probability that a system will perform its function over a specified period of time and under specified service conditions. The study of Structural Reliability is concerned with calculation and prediction of the probability of limit state violations at any stage during a structure's life. The probability of occurrence of an event such as limit state violation is a numerical measure of the chance of its occurring. The probabilistic approach is based on the theoretical foundation of the Probability Distribution Factor (PDF) information and introduces the use of random variables, processes, and fields to represent uncertainty. Various methods of uncertainty analysis are available such as Stochastic Finite Element Method, First Order Reliability Method and Second Order Reliability Method (FORM & SORM), Monte Carlo/ Latin Hypercube Sampling and Random Process/ Field Method [5]. The quantification of reliability levels of structural elements can be accomplished considering one or more failure criteria, such as ultimate strength, yield strength, fatigue strength, etc. [6].

The study on reliability started in early 70's by R.G. Bea [7] of Shell Oil Co.; who structured Reliability Analysis into 5 major parts; namely (1) Loading probabilities, (2) Resistance probabilities, (3) Reliability estimates, (4) Value analysis and (5) Design criteria.

Shell engineers [8] have devised a reliability assessment procedure based on hindcast data and pushover analysis with the help of probabilistic methods, aftermath of Hurricane Camille in the Gulf of Mexico. Their aim of their study was to obtain comparative reliability index and probability failure by conducting pushover analysis on a jacket platform which experienced the Hurricane Camille loading and an extreme loading from hindast data. They have concluded that reliability technique can be confidently applied to problem of optimization of design criteria and reassessment.

T. Onoufriou and V. J. Forbes [9], in their review paper have critically examined the recent developments in system reliability methods for fixed steel offshore platforms. They studied the methods, both deterministic and probabilistic, under extreme loading and also on the treatment of the resistance. Key issues like modeling uncertainties and sensitivities, validation and benchmarking of the methods were also examined. They also highlighted number of technical and philosophical issues which needed to be addressed to increase the benefits from system reliability applications in design and re-assessment of fixed platforms.

Kheiri and Bahaari [10] applied push over analyses and non linear dynamic analyses on two platforms using ABAQUS software for modeling and analysis. They concluded that in non linear dynamic analysis, reserve strength of jacket structures was estimated to be higher than that of static push over and that structure can bear more partial failure before global failure.

Not ignoring the foundation effects on reliability, pile-soil interaction and it's stiffness to identify the overall reliability of a jacket structure was studied by many researchers. Numerical models that incorporate 6 different foundation conditions with actual soil in-situ characteristics were used in pushover analysis by B. Asgarian and M. Lesani [11]

Lateral soil stiffness in marine environment was studied by Matlock [12]. He has indentified variations of soil property with depth, pile deflections, stress-strain at affected soil zone and rate, history and sequence of loading as the factors affecting soil lateral resistance values.

P. Pattaradanai [13] has conducted sensitivity study for Reserve Strength Ratio (RSR) of fixed offshore steel platforms in Thai waters. He studied the sensitivity of varying parameters on RSR and followed by regression analysis to obtain the RSR through computation rather than conducting the lengthy and monotonous pushover analysis.

M. F. N. Azman [1] has conducted research on sensitivity study of environmental load to reliability index by 2 methods, namely Simplified Structural Reliability Analysis (SSRA); a PETRONAS in-house method, and by statistical method using Gaussian distribution function. As a result from the sensitivity study he could compare the results for the purpose of validation and efficiency of the methods.

A. Kolios [14] has studied the whole spectrum of reliability issue involving jacket platforms by analyzing factors affecting reliability from corrosion, member capacity deterioration, different wave theory, member surface roughness, material yield strength, evolution of design codes and standards, stochastic nature of loads and resistance, variability in limit states to different methods like finite element, SESAM computer software, response surface, data regression, and so on.

While the current industry practice is similar to what Azman has done; is to obtain the RSR and reliability index via pushover analysis to determine the level of safety of any jacket facility to help to make decision on the continuous usage of aging jacket platforms.

A. Reserve Strength Ratio

The study on reserve strength ratio was initiated to discuss the sources of reserve and residual strength of 'frame behavior'. H. M. Bolt, Billington C. J., and Ward J. K. [15] suggested the formula as in Equation 1 that tied the ultimate strength and design strength of a platform to its reserve strength ratio.

$$\mathrm{RSR} = \frac{\text{Ultimate Strength}}{\text{Design Strength}} \tag{1}$$

Non-linear pushover analysis is widely used as an analytical tool to evaluate the structural behavior of not only jacket platforms but any forms of structures in the inelastic range and to identify the weakest points of the structure as well as the failure mechanisms [16]. According to Krawinkler, H. and Seneviratna, G. D. [17] pushover analysis is to represent a structure in two or three dimensional models that account for all important linear and non-linear characteristics, apply incremental loads until a target displacement or failure is achieved. Figure 1 shows a simple illustration of a pushover analysis carried out on a two dimensional frame. The jacket platform is pushed till a desired displacement or collapse is obtained. Figure 2 details the different segments of the plotted graph.

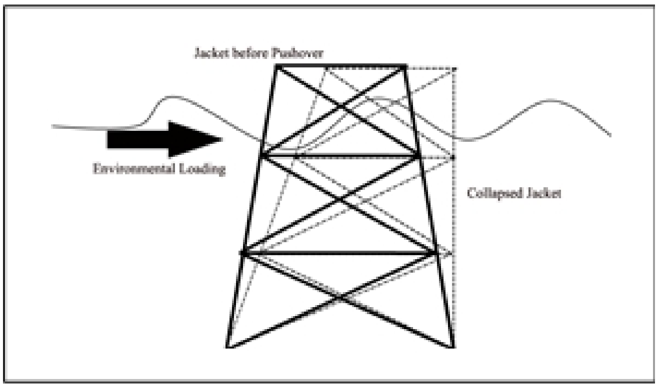


Fig. 1. Typical Pushover Analysis Procedure.

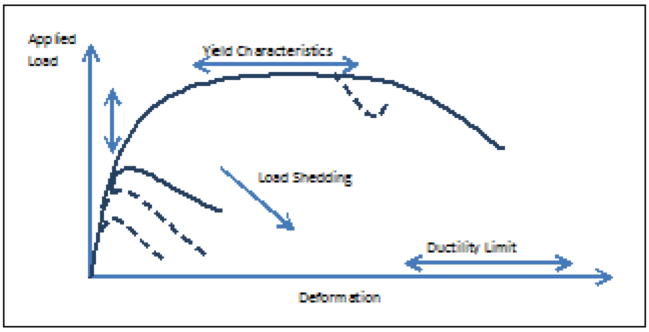


Fig. 2. Non linear curve components. [17]

B. *Pile-Soil Interaction and p-y curve*

Based on API-RP-2A-WSD [19] lateral soil resistance-deflection (p-y) curves should be constructed using stress-stain data from laboratory soil samples. For the lateral bearing capacity for soft clay, pu has been found to vary between 8c and 12c except at shallow depth. pu increases from 3c to 9c as X increases from 0 to XR according to Equation 2 and 3 below:

$$p_u = 3c + \gamma X + J\frac{cX}{D} \qquad (2)$$

$$p_u = 9c \; for \; X \geq X_R \qquad (3)$$

where,

pu = ultimate resistance, psi (kPa)
c = undrained shear strength for undisturbed clay soil samples, psi (kPa)
D = pile diameter, in. (mm)
γ = effective unit weight of soil, lb/in2 (MN/m3)
J = dimensionless empirical constant with values ranging from 0.25 to 0.5 having been determined by field testing. A value of 0.5 is appropriate for Gulf of Mexico clays.
X = depth below soil surface, in. (mm)
X_R = depth below soil surface to bottom of reduced resistance zone in in. (mm). For a condition with depth, Equations 2 and 3 are solved simultaneously using Equation 4 as follows:

$$X_R = \frac{6D}{\frac{\gamma D}{c} + J} \qquad (4)$$

where the strength varies with depth, Equations 2 and 3 may be solved by plotting the two equations, i.e., pu vs. depth. The point of first intersection of the two equations is taken to be X_R. These empirical relationships may not apply where strength variations are erratic. In general, minimum values of X_R should be about 2.5 pile diameter

From the literature, Agarian and Lesani [11] developed numerical models that incorporated different foundations conditions for considering pile-soil-structure interaction to perform a pushover analysis of jacket platform. It was found that the most favorable capacity is achieved when pile-soil interaction is considered in the analysis.

IV. METHODOLOGY

In this paper, the methodology of conducting sensitivity study using pushover analysis is discussed. Load cases made from load combinations, load directional effects and analysis with and without considering pile structure interaction (PSI) was studied. These were studied to assess the impact on reserve strength ratio (RSR). This in return will help to identify parameters which having significant impact on RSR.

A. *Platform Model*

Figure 3 shows Platform X, a 4 pile legged oil producing platform found in the Kumang Cluster, off the coast of Bintulu, Sarawak with a water depth of 94.6m.

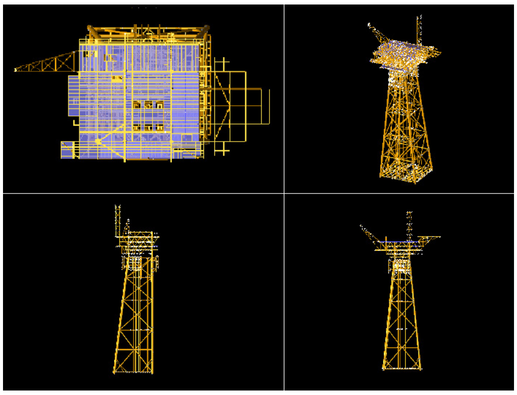


Fig. 3. SACS model of Platform X

B. Sensitivity Analysis

Referring to Table I with an arbitrary direction and fixed storm load case, live load combinations were varied. From the pushover analysis, with 9 live load combinations was observed that the variance in the RSR was insignificant. This is due to the fact that in pushover analysis the gravity load i.e. dead and live loads are acted upon the structure till a factor of 1 and followed by environmental load i.e. storm load till the structure collapses. So when the storm load was fixed and live load combinations were varied, where it was factored until a factor of only 1, the differences in the load combinations were insignificant compared to storm load which is expected to reach to a factor of above 4 or 5. Figure 4 shows this in graphical form for a pictorial observation.

TABLE I. RSR from Live Load Variation and Storm Load Fixed

Load	**Limit of Failure**				**RSR**
	Design Level		**1st Member Failure Level**		
	Load Step	***Base Shear***	***Load Step***	***Base Shear***	
LL01 ST02	15	9359.15	29	35104.66	3.75
LL02 ST02	15	9352.35	29	35097.72	3.75
LL03 ST02	15	9341.36	29	35087.91	3.76
LL04 ST02	15	9234.18	29	35008.66	3.79
LL05 ST02	15	9194.03	29	34940.97	3.80
LL06 ST02	15	8933.38	29	34680.22	3.88
LL07 ST02	15	9185.56	29	34936.75	3.80
LL08 ST02	15	9056.58	29	34801.95	3.84
LL09 ST02	15	9200.64	29	34943.65	3.80

TABLE II. RSR from Storm Direction Variation and Live Load Fixed

Degree	**Limit of Failure**				**RSR**
	Design Level		**1st Member Failure Level**		
	Load Step	***Base Shear***	***Load Step***	***Base Shear***	
0	15	8180.84	24	22485.75	2.75
45	15	9359.15	29	35104.66	3.75
90	15	8798.54	30	35175.93	4.00
135	15	8895.05	26	28808.83	3.24
180	15	9137.98	23	24131.37	2.64
225	15	8733.62	29	33647.99	3.85
270	15	9007.14	25	27019.27	3.00
315	15	8976.04	25	24643.88	2.75

Meanwhile for the case with an arbitrary fixed live load with varied storm direction, the pushover analysis produced very large difference in value for the RSR as in Table II. This shows that load direction plays an important role in determining RSR value. Based on platform north, different directional loads were resisted by different platform directional resistance/ stiffness values. This gives variation both in load and resistance. Hence the RSR values from directional loads were very much volatile compared to other form of variations adopted. Hence the big difference experienced in RSR values as could be seen in Fig. 5.

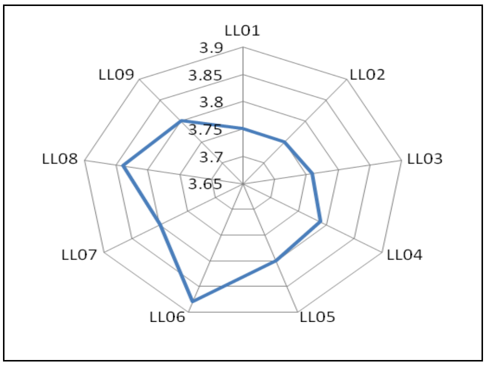


Fig. 4. RSR from Live Load Variation – small variation observed among the load combinations (difference by 0.13)

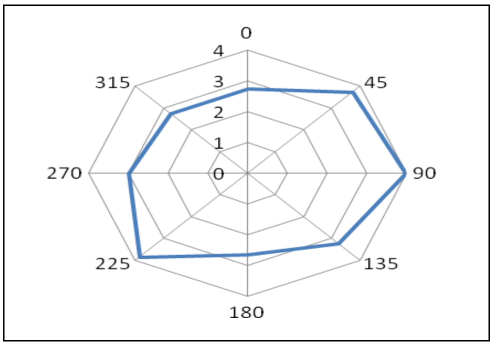
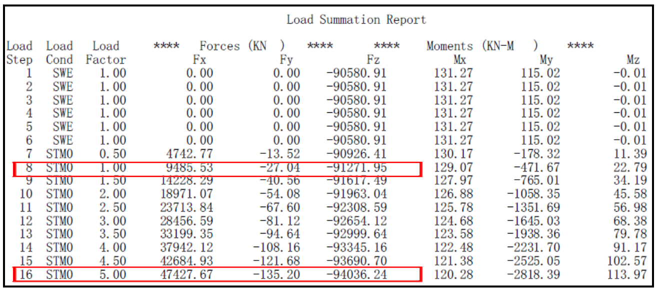


Fig. 5. RSR Storm Direction Variation –big variation observed among the different directions (difference by 1.21)

C. Sensitivity Analysis Considering PSI

For a fixed direction, in this case North (0^o) pushover analysis was done and RSR was obtained taking into consideration the effect of pile soil interaction (PSI) inclusion and exclusion. It was observed that, in general the collapse analysis with PSI input yields lower RSR compared to an analysis without PSI. The reason behind this is due to the nature of the Finite Element analysis where when considering the PSI the jacket platform is modeled with the soil and pile stiffness which has a certain limiting values which when exceed the platform fails or collapses. Meanwhile an analysis without the PSI is done by taking a high soil stiffness value; means the platform end is terminated at the soil level and the soil is assumed as a very rigid structure. Hence the pushed structure will displace until the space truss structure of the platform reaching plasticity followed by yielding and finally collapses. Figure 6 and 7 show the screen shot from SACS for the pushover analysis result for the case with and without PSI, respectively. The RSR value had increased by 15% by including the PSI into the analysis as can be seen in Tables III and IV.



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                                    Load Summation Report

Load  Load   Load       ****   Forces (KN  )   ****       ****   Moments (KN-M   )    ****
Step  Cond  Factor            Fx         Fy         Fz          Mx          My          Mz
  1    SWE   1.00           0.00       0.00   -90580.91      131.27      115.02       -0.01
  2    SWE   1.00           0.00       0.00   -90580.91      131.27      115.02       -0.01
  3    SWE   1.00           0.00       0.00   -90580.91      131.27      115.02       -0.01
  4    SWE   1.00           0.00       0.00   -90580.91      131.27      115.02       -0.01
  5    SWE   1.00           0.00       0.00   -90580.91      131.27      115.02       -0.01
  6    SWE   1.00           0.00       0.00   -90580.91      131.27      115.02       -0.01
  7   STMO   0.50        4742.77     -13.52   -90926.41      130.17     -178.32       11.39
  8   STMO   1.00        9485.53     -27.04   -91271.95      129.07     -471.67       22.79
  9   STMO   1.50       14228.29     -40.56   -91617.49      127.97     -765.01       34.19
 10   STMO   2.00       18971.07     -54.08   -91963.04      126.88    -1058.35       45.58
 11   STMO   2.50       23713.84     -67.60   -92308.59      125.78    -1351.69       56.98
 12   STMO   3.00       28456.59     -81.12   -92654.12      124.68    -1645.03       68.38
 13   STMO   3.50       33199.35     -94.64   -92999.64      123.58    -1938.36       79.78
 14   STMO   4.00       37942.12    -108.16   -93345.16      122.48    -2231.70       91.17
 15   STMO   4.50       42684.93    -121.68   -93690.70      121.38    -2525.05      102.57
 16   STMO   5.00       47427.67    -135.20   -94036.24      120.28    -2818.39      113.97
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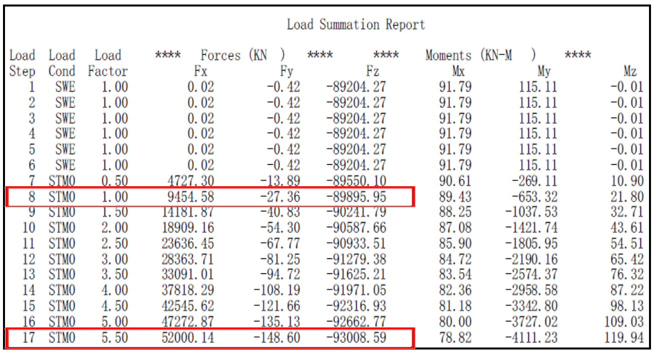
Fig. 6. Screen Shot from SACS – RSR with PSI and Fixed Direction



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                                    Load Summation Report

Load  Load   Load       ****   Forces (KN  )   ****       ****   Moments (KN-M   )    ****
Step  Cond  Factor            Fx         Fy         Fz          Mx          My          Mz
  1    SWE   1.00           0.02      -0.42   -89204.27       91.79      115.11       -0.01
  2    SWE   1.00           0.02      -0.42   -89204.27       91.79      115.11       -0.01
  3    SWE   1.00           0.02      -0.42   -89204.27       91.79      115.11       -0.01
  4    SWE   1.00           0.02      -0.42   -89204.27       91.79      115.11       -0.01
  5    SWE   1.00           0.02      -0.42   -89204.27       91.79      115.11       -0.01
  6    SWE   1.00           0.02      -0.42   -89204.27       91.79      115.11       -0.01
  7   STMO   0.50        4727.30     -13.89   -89550.10       90.61     -269.11       10.90
  8   STMO   1.00        9454.58     -27.36   -89895.95       89.43     -653.32       21.80
  9   STMO   1.50       14181.87     -40.83   -90241.79       88.25    -1037.53       32.71
 10   STMO   2.00       18909.16     -54.30   -90587.66       87.08    -1421.74       43.61
 11   STMO   2.50       23636.45     -67.77   -90933.51       85.90    -1805.95       54.51
 12   STMO   3.00       28363.71     -81.25   -91279.38       84.72    -2190.16       65.42
 13   STMO   3.50       33091.01     -94.72   -91625.21       83.54    -2574.37       76.32
 14   STMO   4.00       37818.29    -108.19   -91971.05       82.36    -2958.58       87.22
 15   STMO   4.50       42545.62    -121.66   -92316.93       81.18    -3342.80       98.13
 16   STMO   5.00       47272.87    -135.13   -92662.77       80.00    -3727.02      109.03
 17   STMO   5.50       52000.14    -148.60   -93008.59       78.82    -4111.23      119.94
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Fig. 7. Screen Shot from SACS – RSR without PSI and Fixed Direction

TABLE III. RSR WITH PSI AND FIXED DIRECTION

Direction	**Reserve Strength Ratio RSR**	**Base Shear 100 yrs wave, current and wind load (MN)**	**Collapse Base Shear (MN)**
N (0 ^{o})	4.769	9.479	45.201

TABLE IV. RSR WITHOUT PSI AND FIXED DIRECTION

Direction	**Reserve Strength Ratio RSR**	**Base Shear 100 yrs wave, current and wind load (MN)**	**Collapse Base Shear (MN)**
N (0 ^{o})	5.499	9.481	52.135

Figures 8 and 9 show the screen shot from SACS, portraying the platform finite element model showing the member stress levels, members reaching and exceeding plastic limit followed by hinge formation. It could be said that, in a PSI included pushover, the pile legs experience a slender column effect where the compression side of the platform allows the pile to buckle. This is agravated further by the failure of the lateral stiffness of the soil from the pushover. Meanwhile for the analysis with PSI, the foundation is in a very stiff condition which allows the truss structure to displace more and eventually let the truss members absorb more internal stresses. This in fact gives more reserve in terms of the strength of the platform, hence the higher RSR value.

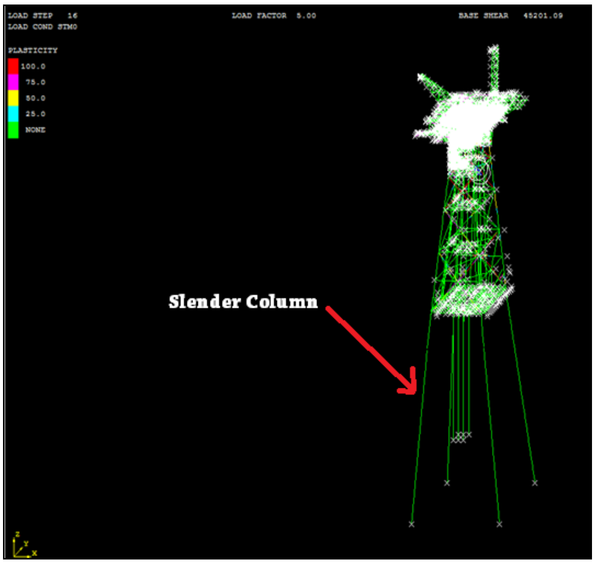

Fig. 8. At Load Step #16 (With PSI), Base Shear 45,201kN – Few Members has Reached Plasticity and Hinged

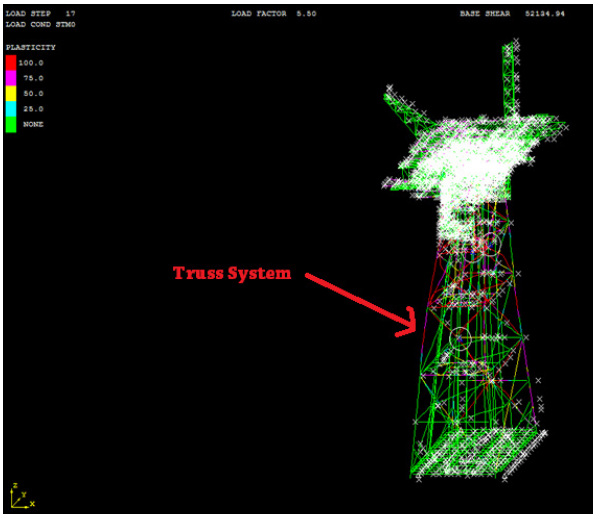

Fig. 9. At Load Step #17 (Without PSI), Base Shear 52,134kN – Many Members has Reached Plasticity and Hinged

On another perspective, a pushover analysis was done taking into consideration all directional effects and PSI inclusion and exclusion effects. As been proven earlier, in general the collapse analysis with PSI input yields lower RSR compared to an analysis without PSI. The RSR has increased from as low as 5.6% to 50.1% as can be seen in Tables V. One outlier was from W (270 ^{o}) where it has recorded a negative increase as much as -10.1% which indicates that the truss effect is much weaker than the slender column effect. This may be attributed to low stiffness of the platform resistance in that direction. Further analysis may be required to prove this hypothesis.

TABLE V. RSR BASED ON OMNI DIRECTIONAL WAVE (WITH PSI)

Direction	RSR with PSI	RSR w/out PSI	Diff. (%)
N (0°)	44.23/9.142 = 4.838	50.343/9.143 = 5.506	13.8
NE (45°)	43.041/8.431 = 5.105	59.006/8.432 = 6.998	37.1
E (90°)	48.065/8.580 = 5.602	60.167/8.581 = 7.011	25.2
SE (135°)	41.935/8.302 = 5.051	53.985/8.302 = 6.502	28.7
S (180°)	41.377/8.779 = 4.713	57.098/8.783 = 6.501	37.9
SW (225°)	32.385/8.094 = 4.001	48.643/8.098 = 6.007	50.1
W (275°)	41.479/8.296 = 5.000	37.350/8.307 = 4.496	-10.1
NW (315°)	46.511/8.188 = 5.680	49.124/8.190 = 5.998	5.6

V. CONCLUSION

The following conclusions are drawn from the sensitivity study results:

1. The live load combinations have not much significance on the RSR values as compared to the variation in storm directions;
2. RSR values from directional loads and resistance are very much volatile and significant;
3. Collapse analysis with PSI yields lower RSR compared to an analysis without PSI. Inclusion of PSI increased the RSR value in the range of 5.6% to 50.1%; some outliers are expected as a result of low stiffness of the platform resistance in that specific direction;
4. A trend called slender column and truss system effects were introduced for the pushover analysis with and without PSI, respectively; and
5. Sensitivity study, in agreement with failure mechanisms experienced in the pushover analysis.

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