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An Investigation into the Failure of Pinion Holding Capacity, Joint Cans of a Leg Structure, and Preload Tank Capacity of a Jack-Up Rigby Using Finite Element Method

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Abstract:
The joint can assessment analysis has been performed to investigate the failure of the leg lattice structure of the legs of a Jack-up Rig which is being converted from Mobile Offshore Drilling Unit (MODU) to Mobile Offshore Production Unit (MOPU). The primary objective of this study is to check whether the existing joint cans of the legs of a jack up rig can reliably support the increased elevated load when converted as production platform.
The Finite Element Method is used to determine the stresses and strains in various joint sections of the leg lattice by modelling the entire rig structure in SACS modelling and FE analysis software which is extensively used in offshore industry. A detailed penetration and foundation stability analysis is subsequently carried out by using the leg reactions of elevated analysis accounting soil fixity. This present study addresses the overturning stability of the unit, preload requirements and the structural integrity of the legs and the leg holding system (pinions) under storm loading. It is found that the preload tank capacity and pinion holding capacity are in-sufficient to support the required preload reactions due to the increased load after conversion as a production platform and suitable remedial measures have been suggested by considering the overall overturning stability and based on site specific conditions and increased air gap between the water level and the bottom of pontoon of the rig.

Keywords: *Pinion Stiffness, Leg Strength Analysis, Elevated Load, Jack Up Rig, Mobile Offshore Drilling Unit (MODU), Mobile Offshore Production Unit(MOPU), Met-Ocean data, Geo-Technical Studies, Stress, Displacement, Chord Pipes, Bracing Pipes, Leg Penetration, Air Gap, Overturning stability, Dynamic Amplification Factors (DAFs), Site Specific Studies, Drag Coefficient (C_d), Inertia Coefficient (C_m), Pinion strength.*

1. Introduction

The Rig under this study is a three-legged Jack-up Rig which was built in 1981, classed as Mobile Offshore Drilling Unit (MODU) under ABS Class. It has performed as drilling rig in various locations in the past. Presently the rig has been decided to be converted into Mobile Offshore Platform Unit (MOPU). This jack-up has three square Z-braced truss legs with internal cross span-breaker bracing. Each leg has two diagonally opposed driven chords and two diagonally opposed un-driven chords. The driven chords are of the split-cylinder type with a centre-plate and opposed (double-sided) racks. The un-driven chords are cylindrical. This study did not address accidental or earthquake loading. It only addresses for installations of rig with different water depths and soil conditions with 25 years' wind data, 50 years' wind data and 100 years' wind data at the site specific conditions. No assessment of the interaction between the jack-up's spud cans and the adjacent fixed platform structure was made, nor of the interaction between the jack up's spud cans and any seabed irregularities. More details on the co-ordinates of and water depth studies of the study area have been presented in the form of a technical paper published by the same authors (Reference#1).
The principal dimensions of the Jack-up rig under this study are shown in Table-1 below.

PARAMETER	VALUE
Length of Hull (m)	71.97
Breadth of Hull (m)	83.10
Depth of Hull (m)	7.00
Leg Length (m)	128.85
Longitudinal Leg Spacing (m)	55.40
Transverse Leg Spacing (m)	63.97
Leg Chord Spacing (m) (from centroid to centroid)	7.00
Leg Bay Height (m)	4.05
Spudcan Effective Diameter (m)	13.28
Distance from Spudcan Tip to Maximum Bearing Area (m)	1.54
Maximum spud can contact area (m^2)	138.59
Spud can Height (m)	3.735

Table 1: Principle Dimensions of the Jack-up Rig

Figure 1 below indicates the General Arrangement of the Jackup drilling unit under investigation.

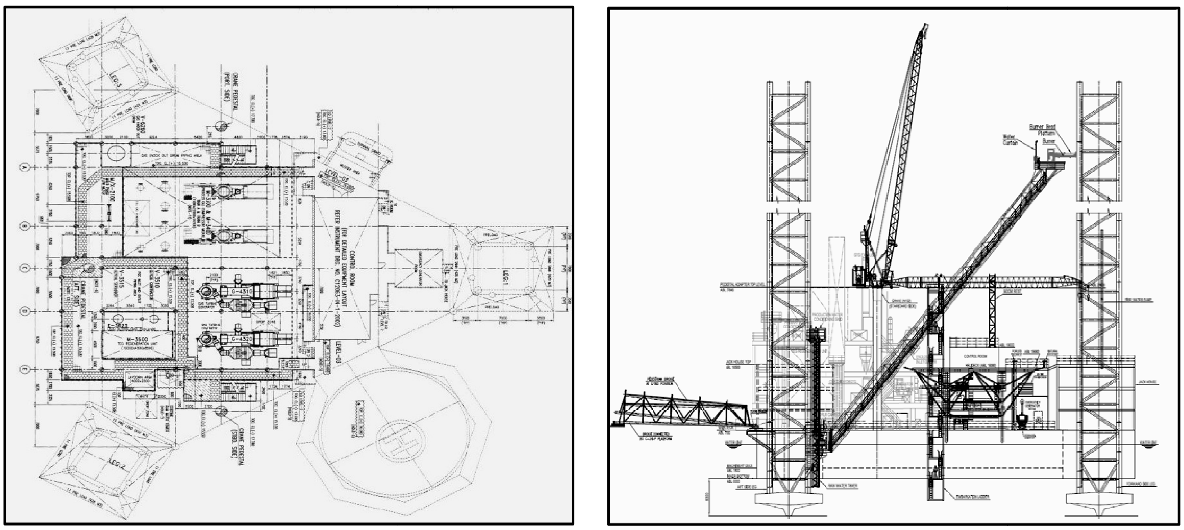

Figure 1: General Arrangement of Rig.

1.1 Scope of Work

The rig under study is a three-legged self-elevating jack-up unit designed for a water depth of up to 300 feet (92 m approximately). Each leg has four chords truss framed with bracings all being tubular members. The scope of work for the present study is to carry out following;

i. To verify that the leg lattice structure reliability and whether it supports the total elevated load in a specified environment for site specific conditions throughout its life.
ii. To evaluate the leg strength considering all relevant, realistic load conditions and combinations.
iii. To check the overturning stability, storm holding capacity requirement in line with member strength.

To achieve the above tasks, the extreme wave analysis with dynamic effects included for Jack-up Rig have been carried out in the Structural Analysis Software, SACS 5.5.

2. Approach to the Problem

To perform the site specific assessment of the Rig, the two-step procedure given in ABS guidance notes (Ref #1) has been used. The legs are modelled to be supported at the bottom by means of linear rotational, vertical and horizontal springs. The initial rotational, vertical and horizontal stiffness values at each leg footing are calculated in accordance with ISO 19905-1 (Reference #2) by assuming the partial penetration of spudcan in the sand. These effective foundation stiffness values are used to calculate the natural periods of the jack-up unit and also for performing the random wave dynamic analysis for determination of Dynamic Amplification Factors (DAFs).

P-Delta (P-Δ) loads are included in the analysis using respective load cases. Gravity loads like elevated weight, leg weight, caisson & pump weight and overall buoyancy are considered as P-delta load cases.

To account for the irregularity of wave surface and wave spreading, wave kinematic factor of 0.87 has been considered as per guidelines of ISO 19905-1. The spud cans have been modelled as rigid dummy members and the hydrodynamic loads on spud cans are excluded since the spud cans are penetrated deep within the soil. Wind force and moments on the hull are calculated using the block area method and shape & height coefficients given in ABS MODU Rules.(Reference#3). The 3D FE model of the rig is as shown in the Figure 2 below.

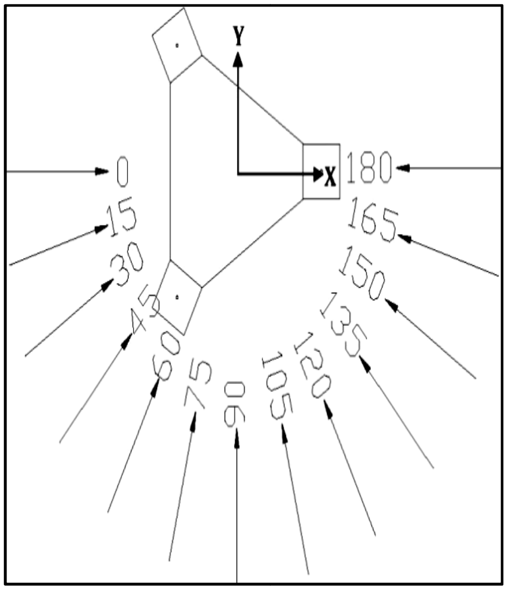

Figure 2:Three-Dimensional FE Model of the Rig.

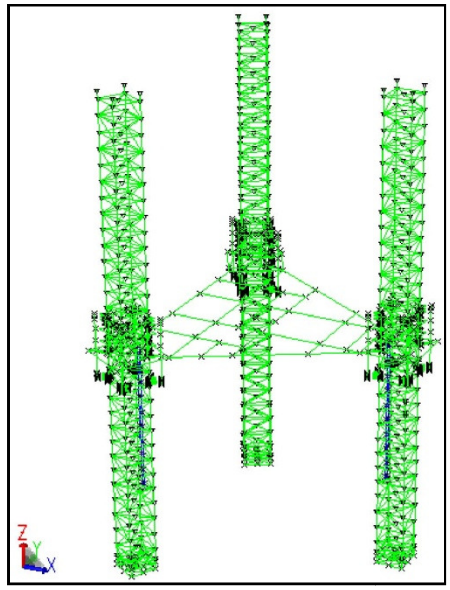
Figure 3: Picture indicating Storm Heading

2.1. Specifications for Analysis

Table-2 below shows the specifications given for carrying out the Rig Elevated Analysis.

Elevated lightship	5617 tons
Variable weight	1250 tons
Leg Self weight	2190 tons
ENVIRONMENTAL CONDITIONS:	
Water depth	50 m
Wind Speed	191.88 km/hr (103.6 knots)
Wave Height	13.42 m
Wave Period	12.00 sec
Spud can penetration	3.75 m
Current speed varies with height as below.	
0.00 m	0.0 m/s
47.0 m	0.257 m/s
50.0 m	0.514 m/s

Table 2: Specifications for Analysis

3. Model Description

Two models have been used to perform 2-step analysis of the jack-up unit under this study.

i. An Equivalent model to perform the random wave dynamic analysis for deriving the Dynamic Amplication Factors (DAFs).

ii. A detailed model to perform a static structural analysis for deriving the stresses for unity checks.

In the equivalent model the leg is modelled as a series of collinear beams. The cross sectional properties of these beam elements have been derived by using the formulae given in the ABS guidelines for self-elevating units (SEUs) (Reference No.3). Each chord has a diameter of 960 mm (OD) and 46mm thickness and each bracing has a diameter of 257.3 mm (OD) and a thickness of 28mm. The legs in both models are assumed to be supported at the bottom by means of linear rotational, vertical and horizontal springs.

The analysis presented in this paper has been performed for 0^0 to 180^0 storm headings with respect to jack-up rig at an interval of 15^0 as indicated in the figure-3 below.

A high degree of accuracy in the analytical method has been used. Legs are modelled as discrete beam elements.

The estimated effective foundations stiffness values are used to calculate the natural periods of the jack up unit and also for performing the random wave dynamic analysis for determination of DAFs.

Figure 4 below indicates the FE Model with equivalent model case.

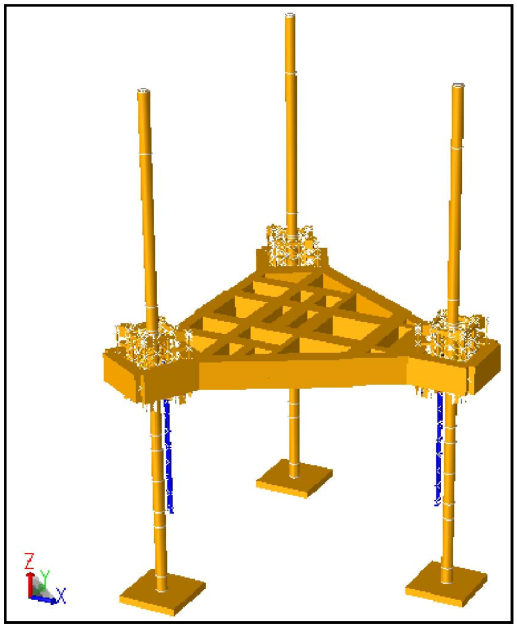

Figure 4: Equivalent Model for Random Wave Analysis

In the detailed model, each member of the truss leg is modelled individually with their respective geometric properties.Figure 5 below indicates the FE Model with detailed model case.

Figure 5:Detailed Model for Non-linear Quasi Static Analysis

Hull Structure is modelled as a grillage of beam members. The properties of the beams are calculated based on the depth of the bulkheads and side shell and the effective width of deck and bottom plating. In the calculation of overall global hull section properties, local Ay, Ix &Iz for all continuous longitudinal and transverse members is calculated by considering the hull section as box girder whereas local Ax, Az and Iy for all continuous longitudinal and transverse members are calculated by considering them as I-sections/C-sections with web as depth of bulkhead and flange as effective attached plating of main deck and bottom.

3.1. Spud Can Modelling

For the analysis spud can is modelled as flat circular foundation. The effective diameter is calculated from the actual spud can cross section in contact with seabed surfaces. Spud can dimensions are shown in Table-3 below. Spud can geometry is shown in figure-6 below.

Geometrical Properties	Value
Shape	Octagon
Length of a side	5.36 m
Max. Vertical Projected area	140.00 m^2
Effective Diameter	13.39 m
Depth of pud can (Ht)	3.70m
Top Diameter	1.22 m
Max. Laterally Projected Area	26.30 m^2

Table 3: Spud can dimension

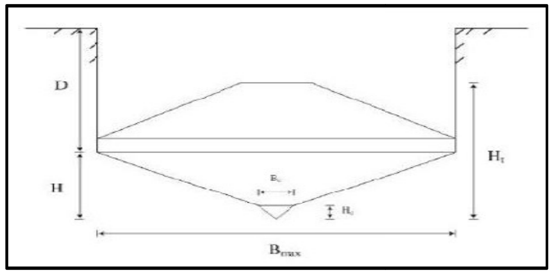

Figure 6: Typical SpudCan Geometry

4. Geo-Technical Study of the Site

Based on the soil data collected for site specific for the rig, it comprises of 11.5m of very soft to soft clay overlaying 8.5m medium to fine grained sand upto a depth of 21.0m. This is underlain by a 9.0m thick layer of very dense sand to a depth of 30.0m below the seabed surface. The soil stratum is modelled using specified design parameter and BOR log chart of soil. The friction angle of soil is reduced by 5 degrees for the friction angles between 30 deg to 40 deg. as suggested for large diameter spud cans in ISO &SNAME. Vertical bearing capacity is calculated at various spudcan tip penetrations below seabed using bearing capacity solutions given in ISO 19905-1. The total ultimate vertical bearing capacity is then converted to available structural spudcan reaction V_L by deducting submerged weight of backfill during preloading, Wbf0 and adding soil buoyancy of spud can below bearing area Bs. The following formula from ISO 19905-1 (Ref#2) has been used.

$$V_L = Q_v - W_{BF,O} + B_S$$

A graph of VL vs. spudcan tip penetration is plotted as shown below (Fig.7)

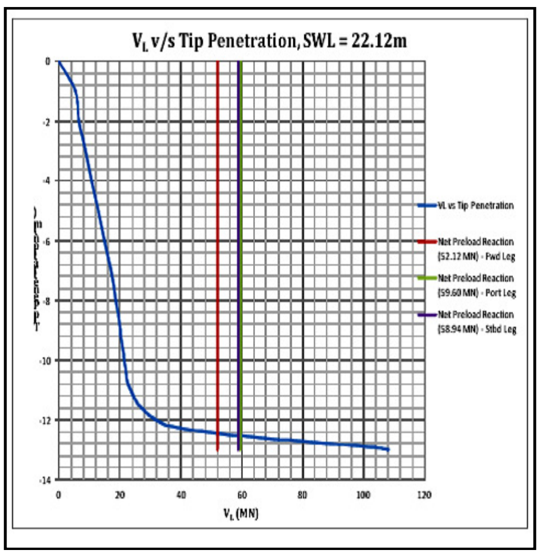

Figure 7: Spud Can Reaction vs. Tip Penetration

4.1. Drag and Inertia Co-efficient Values

Morrison's equation is applicable for calculating the hydrodynamic wave loads on the legs of the rig because the diameter of the chord is less than 20% of wavelength of design wave. The Figure 8 below indicates the sketch of the chord pipe with rack showing its dimensions for calculation of drag and inertial coefficients.

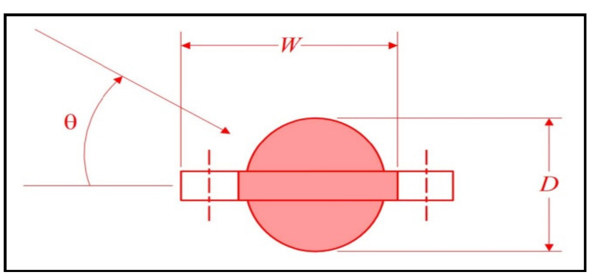

Figure 8: Drag & Inertia Coefficients

A summary of the drag and inertia coefficients for leg members of the detailed truss leg model is tabulated below (Table-4).

Member	Heading	Smooth		Rough	
		C_D	C_M	C_D	C_M
Chord w/o Rack	All	0.65	2.0	1.0	1.80
All Braces	All	0.65	2.0	1.0	1.80

Table 4: Drag & Inertia Co-efficient values

5. Loading Combination

Loading combination for 0 to 180^0 in storm condition is considered as mentioned below;

Load combination = ELWT (Elevated weight) + LGWT (Leg Weight + Buoyancy) + SPUD (Spud weight) +RWT4 (Caisson & Pump Weight) + S000(Wave + Current) +H000(Wind on Hull) +W000(Wing on legs) +I000(Dynamic Inertia Loads) +PDELTA

6. Governing Equations

Ultimate vertical / horizontal / rotational capacity interaction function for spud cans in sand and clay is given by the following formula. (This is the formula for fully or partially penetrated spudcans).

$$\left[\frac{F_H}{Q_H}\right]^2 + \left[\frac{F_M}{Q_M}\right]^2 - 16(1-a)\left[\frac{F_V}{Q_V}\right]^2\left[1-\frac{F_V}{Q_V}\right]^2 - 4a\left[\frac{F_V}{Q_V}\right]\left[1-\frac{F_V}{Q_V}\right] = 0$$

For shallow embedment for sand value of ‘a’ tends to zero, then the yield interaction formula takes the following form.

$$\left[\frac{F_H}{Q_H}\right]^2 + \left[\frac{F_M}{Q_M}\right]^2 - 16\left[\frac{F_V}{Q_V}\right]^2\left[1-\frac{F_V}{Q_V}\right]^2 = 0$$

Q_v = The gross ultimate vertical bearing capacity of the soil beneath the spudcan.
= Net preload reaction + $W_{BF,O}$+ B_S
F_v = the gross vertical force acting on the soil beneath the spud can due to applied load case including the efforts of backfill during preloading and spud buoyancy
F_H = the horizontal force applied to the spudcan due to the applied load case.
F_M = the bending moment applied to the spud can due to the applied load case.

7. Details of Design & Analysis

Equivalent Leg model is used to perform the random wave dynamic analysis. Following steps outline the random wave dynamic analysis procedure in brief.

7.1. Preliminary Design Calculations

The preliminary design calculations for member stresses have been carried out using the governing equations.

7.1.1. Marine Growth

Leg region from 6m above mean water line (MWL) to mud line is assumed to be rough (fouled) for the appropriate drag and inertial coefficient. Remaining leg region is assumed to be smooth. As such the marine growth is considered as “zero” in general due to the reason that owners/operators will maintain the rig well for next five years with proper Marine Growth Prevention System (MGPS) and anodes calculated and fixed for next seven and half years. During next operational site change, the anodes and MGPS will be changed to cater to next period of operation.

7.1.2. Analysis Procedure

1. The soil stratum is modeled using bore log chart.
3. Vertical bearing capacity is calculated at various depths below the seabed using bearing capacity solutions.
4. A graph of vertical bearing capacity v/s depths below the seabed (penetration) is plotted and used to determine penetration achieved during preloading.
5. The soil is checked for punching and squeezing phenomenon and accordingly vertical bearing capacity is corrected.
6. A corrected graph (vertical bearing capacity v/s penetration) is plotted and used to assess whether the site has a potential danger of punch through failure and to determine the long term penetration considering squeezing.
7. Leg reactions obtained from elevated hull analysis is used to calculate the leg reaction during preloading.
8. Penetration analysis is carried out by entering the vertical bearing capacity graph with the preload leg reaction and obtaining the corresponding leg penetration.
9. The vertical, horizontal and combined bearing capacity envelopes for pinned footing were obtained using appropriate bearing capacity solutions.

10. A pinned footing elevated analysis is carried out to arrive at the initial leg reactions, penetration and preload requirements.
11. The soil foundation is also checked at every leg for any potential fixity or rotational stiffness based on pinned footing reactions.
12. The footing reaction obtained at every leg is independently checked against a yield surface (moment capacity envelope) solution to evaluate the potential soil fixities. If the foundation is found to lie inside the yield surface, then a potential partial moment fixity exists and otherwise not.
13. An elevated analysis considering the soil fixity is carried out subsequently towards arriving at the final leg reactions, penetrations and preload requirements.
14. Initial Vertical (K1), horizontal (K2) and rotational stiffness (K3) are calculated based on static reactions.
15. The rotational stiffness is applied to the legs with potential fixity and the vertical & horizontal stiffness are applied to all the legs in the elevated model.
16. An updated elevated analysis is carried out with the above calculated stiffness values and step 12 is repeated.
17. In case the foundation is found to lie outside yield surface, the rotationalstiffness is arbitrarily reduced to comply with the yield surface solution.
18. Steps 15 to 17 are iteratively repeated till the soil rotational stiffness atevery leg converges and lies within the yield surface.
19. In case the rotational stiffness at the leeward leg is found to be zero duringconvergence (pinned footing) and the foundation is found to be lyingoutside yield surface, the foundation capacity of the same is additionallychecked as required for a pinned footing based on the maximum legreaction vector.
20. In case the rotational stiffness of the windward leg is found to be zeroduring convergence (pinned footing) and the foundation is found to belying outside yield surface, additionally a sliding check is performed forthe same as required for a pinned footing.
21.The minimum preload tank capacities required are found from the requiredpreload leg reactions.
22. The minimum preload tank capacity for each leg is checked against the availablenet preload tank capacity considering the tank filling levels during jackingcondition.
23. The holding load on each leg is obtained from the preload reactions bysubtracting leg weight in water.
24. The leg holding load is checked against the holding capacities of the pinions.

8. Summary of Results

Based on analysis done as per the procedures set out in section 7.0, the results of analysis are consolidated into a table and presented below (Table-5). A summary of criteria for which the critical parameters are safe and the corresponding values calculated from the analysis are tabulated in this table. The result of whether a particular aspect is satisfactory or not is also indicated in the last column of this table. In the present case, through FE analysis it has been noticed that the cracks may be developed in some tubular members where stress concentration factors are found to be high.

S. No	Parameter	Concerned Area	Sufficiency Criteria	Calculated Value	Result
1	Overturning Stability	Whole Unit	>1.10	2.10	Satisfactory
2	Preload Tank capacity requirement	Fwd Leg	<1070 t	1340 t	Not satisfactory
		Port Leg	<1850 t	2160 t	Not Satisfactory
		Stbd leg	<1760 t	1060 t	Satisfactory
3	Preload Holding Capacity Requirement (Based on available Preload)	All Legs	<4800 MT per leg	4990 MT per leg	Not Satisfactory
	Preload Holding Capacity Requirement (Based on Required Preload)	All Legs	<4800 MT per leg	4958 MT per leg	Not Satisfactory
4	Storm Holding Capacity Requirement	Pinions	<400 MT per pinion	640 MT per pinion	Not Satisfactory
5	Member Strength	Chord w/o Rack	<1.00	1.49	Not Satisfactory
		Chord with Rack	<1.00	1.44	Not Satisfactory
		Diagonal Brace	<1.00	2.26	Not Satisfactory
		Horizontal Brace	<1.00	0.88	Satisfactory
		Internal Brace	<1.00	0.89	Satisfactory
6	Joint Strength	Chord-Diagonal Brace	<1.00	212 *	Not Satisfactory
		Chord – Horizontal Brace	<1.00	517 *	Not Satisfactory
		Chord-Internal Brace	<1.00	212 *	Not Satisfactory
		Internal Brace-Internal Brace	<1.00	1.86	Not Satisfactory
* The high UC values which are higher than 200 do not represent the true UC Value. This is the value output by SACS when excessive chord stresses result in negative allowable stress as per joint strength check formulation of API RP 2A (Ref.7). This however indicates that the join needs to be redesigned.					

Table 5: Results of Analysis

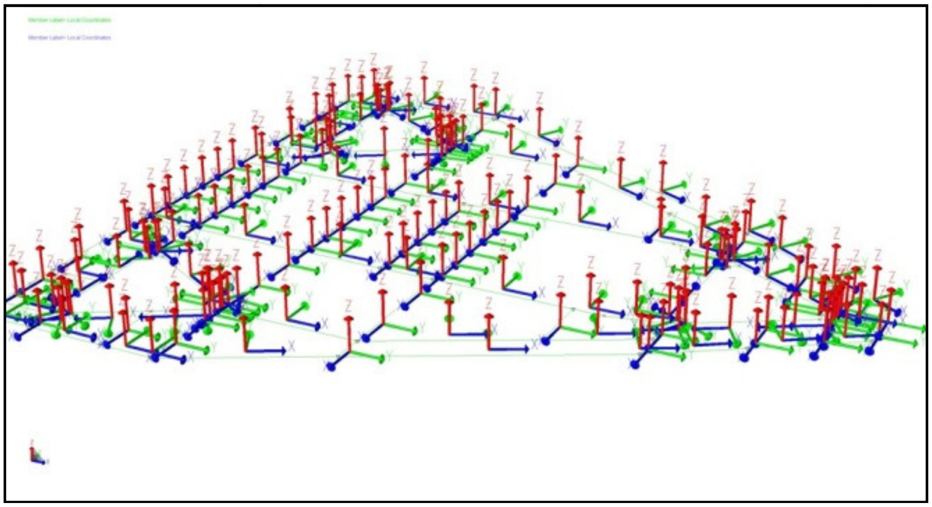

Figure 9

9. Conclusions

(i) The following conclusions are drawn from the analysis presented herein.
(ii) The expected spudcan tip penetration is approximately 12.55m which is achieved by preloading all the tanks to their full capacity.
(iii) Based on the site specific leg analysis the global strength of the existing leg is found to be insufficient for 9500 MT elevated weight, i.e., lightship weight + variable load. Suggested rectification for this problem is to reinforce the leg in way of the leg-hull interface by increasing diameter and thickness for about 30m height of each leg which traverses by having leg to hull interface in most of air gaps during installation as shown in the figure below.

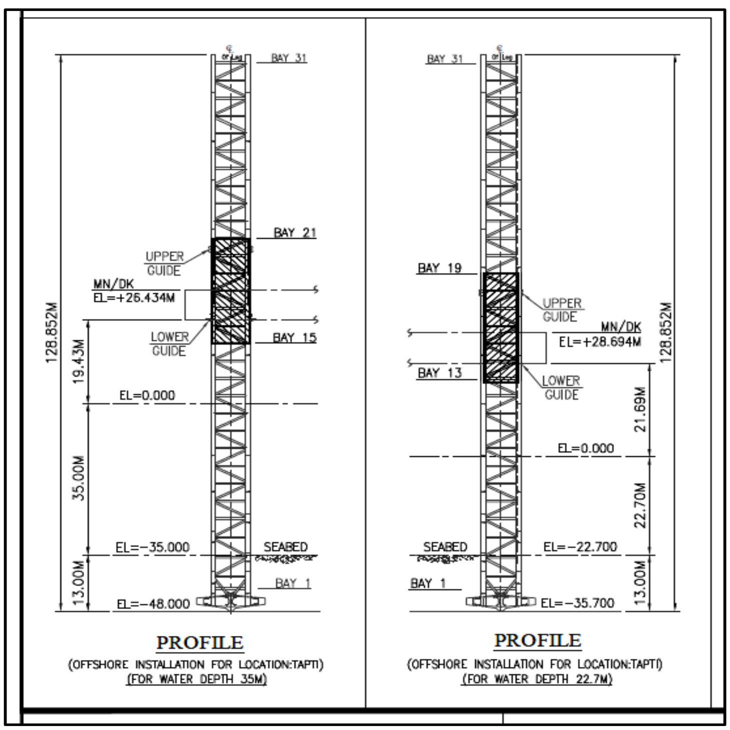

Figure 10: Leg Reinforcement Suggested

(iv) The reaction arm structure (i.e., beam welded on the block guide) is just acceptable for the new loading.
(v) To avoid these problems, during refurbishment it is advised to install a new beam structure with an increased strength. The improvement can be obtained by using a new steel material such as S275J2 or S355J2 according to NF EN 10025. By this way, it will increase the margin to about 1.30.

10. Acknowledgements

Authors are thankful to Pipavav Shipyard Limited Authors are also thankful to all the project members involved in the Conversion project of the ONGC Rig 'Sagar Pragati'.

11. Nomenclature

H [m]	Wave Height
D [m]	Water Depth
T [sec]	Wave Period
g [m/sec^2]	acceleration due to gravity
E [N/mm^2]	elastic modulus of the material
FH /QH =	Horizontal foundation Capacity
FVH =	Vertical foundation capacity in combination with horizontal load
FV =	Vertical foundation Capacity
M =	Reaction Moment

12. Greek Conventions

ϕ' = Friction angle
ϒ' =Effective unit weight

13. References

i. Study on Failures of leg lattice structure when offshore drill rigs are being converted from mobile offshore drilling units (MODU) mobile offshore production units (MOPU), by Bh.Nagesh, Prof.I.N. Niranjan Kumar & Dr. Manu Korulla. Published in ISSN 2278-0211, Vol-5, Issue-7, Jun-2016.
ii. International Standard ISO 19905-1 (15 Jan 2016) 'Petroleum and Natural gas Industries. Site-Specific Assessment of Mobile Offshore units' Part1: Jack-ups.
iii. American Bureau of Shipping (Effective 1 January 2014). 'Rules for Building and Classing Mobile Offshore Drilling Units'.
iv. American Bureau of Shipping (February 2014, Updated September 2014). 'Guidance Notes on Dynamic Analysis Procedure for Self-Elevating Units'.
v. "Guidelines for Site Specific Assessment of Mobile Jack-up Units" SNAME T&R 5-5A.
vi. ABS, RP-2A, WSD, Recommended Practice for Planning, Designing and Constructing Fixed Offshore Platforms – Working Stress Design, 21st edition, supplement 1-3.
vii. American Institute of Steel Construction (1989), 'Manual of Steel Construction - Allowable Stress Design', Ninth Edition.
viii. "ABS Guidance Notes for Dynamic Analysis of Self elevating – Drilling Units" January 2004.
ix. MSL Engineering Ltd (2004). "Guidelines for jack-up rigs with particular reference to foundation integrity." Retrieved 1 Feb 2008, from,www.hse.gov.uk/research/rrhtm/rr289.htm.
x. "An investigation into the failure of leg-lattice structure of a jack-up rig in relation to site specific condition, using finite element method, when elevated load of the rig has been increased", by Bh. Nagesh, Prof.I.N. Niranjan Kumar & Dr. Manu Korulla. Accepted for publication in IJIRT.