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INELASTIC STATIC PUSHOVER ANALYSIS OF FIXED JACKET TYPE OFFSHORE PLATFORM WITH DRILLED AND GROUTED PILES

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Abstract - *Offshore platforms are giant structures used for the purpose of drilling and extracting the gas and oil from wells, located deep beneath the sea/ocean floors. These platforms have onsite processing and storage facilities, as well as provide accommodation for the crew. Metacognition in reservoir assessment, recovery techniques, subsea technology, extend field life and inflict high demands on existing offshore platforms to support additional vertical and lateral loads. Considering the future requirements for the service life and extended life of the platform, company demands engineering contractor to assess the platform at green field stage of the project with the increased load. Quantitative structural integrity assessment is performed through pushover analysis by using SACS software by modeling the geometry, load application and foundation modeling. The focus of this case study is to analyze the fixed offshore jacket wellhead platform with drilled and grouted piles for 100 year return storm wave, current and wind load applied incrementally up to the collapse of the structure for identifying the collapse load factor or reserve strength ratio (RSR). For finding the RSR, Inelastic Static pushover Analysis is performed using the options available on the software which can take inputs and load details accurately. From the analysis it is observed that first hinge formation is not the limiting capacity of the platform. Further, it observed that platform possesses strength in excess of the original design gravity and environmental loads. The results of this case study are shown in brief.*

***Key Words*: Fixed Offshore Jacket Type wellhead Platform, FEM Design, SACS Software, Pushover Analysis, Plasticity, and Reserve Strength Ratio (RSR).**

1. INTRODUCTION

Offshore platforms are constructed to produce the hydrocarbons oil and gas. It provides safe working environment for the equipment and crew who operate the platform. Offshore structures are classified into three broad categories namely fixed platforms, floating structures, gravity based structures. Fixed jacket type of platform structures are appropriate in shallow water depths. These structures are fixed to sea-bed by means tubular piles either driven through the legs of jackets or through skirt sleeves attached to the bottom of the jacket or drilled and grouted piles. Since the jackets are expensive in terms of the investment for engineering, material procurement for fabrication, construction, installation. Hence, it is required to ensure the structural integrity of the platform in all the aspects during the service life of the platform. The service design life of the offshore platform in subcontinent and Middle East is in the range of 25 - 30 years.

Metacognition in reservoir assessment, recovery techniques, subsea technology, extend field life and inflict high demands on existing offshore platforms to support additional vertical and lateral loads. Many of the early installed platforms are still in service. Over the past two decades, the structural integrity assessments have been carried out on the platforms for its safety and usability beyond the design life. At present, the Oil and Gas company requirement to perform the quantitative structural integrity assessment of the platforms during the green field detailed engineering phase based on expected loads during the service life of the platforms as per the company design criteria as well as APIRP 2SIM[2]. Quantitative structural integrity assessment can be performed through pushover analysis by using SACS software by modelling the geometry, load application and foundation modelling. In this study a typical four legged jacket-type offshore platform is investigated for its structural response by performing inelastic non-linear pushover analysis with wave environment at the green field stage. The analysis is performed using finite element software, SACS, which is widely used in practice for geometric modelling, loading application and modelling soil-pile interaction.

1.1 Offshore Structures

Offshore structures are located in water depths ranges from shallow to deep water depth. The type of offshore structure is mainly depends upon the water depth and environmental conditions. The structural arrangement of the platform intern depends on the above conditions and functionality of the platform. The offshore structures are broadly classified into three categories based on their foundation concepts.

1. Fixed Platforms
    - Jacket / Template type structures
    - Compliant Structures
2. Floating Structures (Buoyant but moored)

- Articulated Tower
- Tension Leg Platform
- Spar Platform
- Floating Production, Storage and Offloading System

3. Gravity Based Structures

- Subsea System

1.2 Inelastic Static Pushover Analysis Overview

Recent developments in the response of the jacket platform structure to extreme environmental condition (100 return period storm wave) require the prediction of the reserve strength capacity. All the structural elements are assumed to be rigidly connected while performing the analysis. As per API RP 2A [1], the ultimate strength of the platform can be assessed by inelastic pushover analysis. Lloyd and Clawson [3] discusses the sources of reserve and residual strength of frame behavior. Marshall [4] studied the behavior of elastic element and ultimate strength of the system.

Recent investigation shows that static pushover analysis generally suffices to demonstrate a structure's resistance to the cyclic loading of the full storm. As per the requirement from the company to perform the integrity assessment in the event of extreme loading scenarios with analytical tools to predict the system reserves beyond the individual component failure capacities. Reserve strength is defined as the ability of the structure to sustain loads in excess of the design value. RSR introduced by Titus and Banon[5] as below.

RSR =$(Ultimate\ Platform\ Resistance)/(Design\ load)$

In fixed offshore structure the load spread is through network of paths. Hence, the failure of a single member does not lead to catastrophic failure of the platform structure.

Reserve strength is evaluated by applying the maximum loading from an extreme event and then performing the static pushover analysis. Static pushover analysis is the application of a single load applied to the structure which is incremented in steps until collapse. Under the incremental loading, the structure converts into elasto-plastic range, yielding of the members occurs thereby reducing the stiffness and introducing permanent plastic deformations. Under cyclic load, the yield repeats causing incremental collapse of the structure.

2. METHODOLOGY

The scope of work includes the study on new fixed offshore wellhead platform.

- To ease the difficulty arising in collapse Analysis of offshore structures using popular software called SACS, which is being largely used by most of the people in the world.
- Collapse analysis of four legged fixed jacket type wellhead platform with drilled and grouted piles and evaluation of the Reserve Strength Ratio as per the company guidelines.
- Reducing time of analysing complex offshore structures by using software as the interface

2.1 Platform Overview

Platform is a 4-legged drilled and grouted pile wellhead platform. One boat landing is on the platform north face. Two riser protectors, one on the east and the other on the west face of the platform. One conductor protector on the south face of the platform. Two number J-tubes, one on the eastside of the platform and the other on the west side of the platform. Three number of risers, one on the west side of the platform and two on the east side of the platform. Twelve conductors on the south face of the platform.

The topside comprises of the helideck (EL +34.50m), building roof(EL +31.50m) main deck (EL +26.0m), production deck (EL+20.0m), cellar deck (EL +16.0m), drain deck (EL +9.0 m), one stair tower on west side of the platform and one vent boom on the south side of the platform. The 3D model of the platform is shown in Figure 2.1.1. The details of the platform are in given Table 2.1.1.

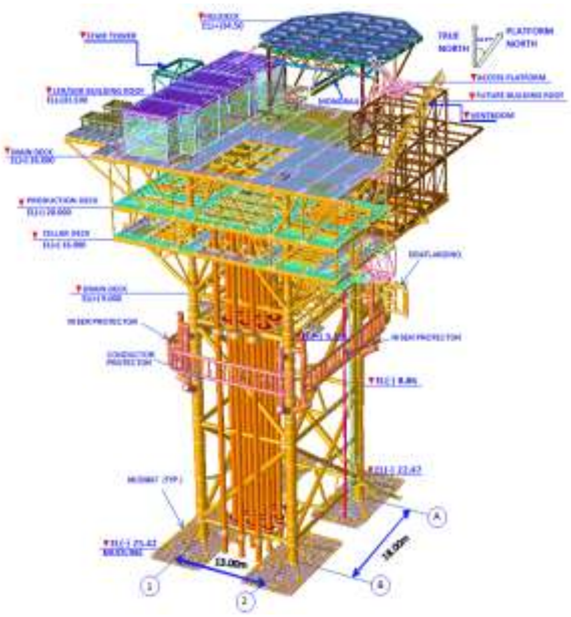


Figure-2.1.1 3D View of the Wellhead Platform

The major facilities support by each deck level as per the plot plan as follows. Main deck supports local equipment room/ switchgear building, heat ventilation and air conditioning (HVAC) units, transformers, vent boom structure and helideck. Production deck supports corrosion inhibitor package, battery room and production choke manifolds. Cellar deck supports piping manifolds and pig launcher/receiver. Drain deck supports drain sump tank and drain pump.

Table -2.1.1 Platform Details

Description	Platform
Structural Function	Wellhead Platform
No of Piles	4
No of Conductors	12
No of Anodes	57
No of Boat Landing	1
No of Riser Protectors	2
No of Conductor Protectors	1
No of J-Tubes	2
No of Risers	3
No of Mudmats	4
Pile Depth below seabed	66 m – A1and A2 Grid Pile 40 m – B1 and B2 Grid Pile
Local Equipment Room /Switchgear Building	1
Deck Levels	5
Water Depth at Mean Sea Level	25.42 m
Minimum Water Depth	24.37 m
Maximum Water Depth	26.90 m

2.2 Three-Dimensional Finite Element Method Model of Platform Structure

2.2.1 Model

The objective of the quantitative analysis is to estimate the RSR of the platform. The program SACS (Structural Analysis Computer System) is used to perform the 3-dimensional finite element method analysis described in the study was developed by EDI (Engineering Dynamic Inc). The full plastic collapse module is used for the purpose of determining the collapse load.

The inputs to this model are properties of all the structural members, connections including the piles, gravity loading, environmental loading including the magnitude and direction, the behavior of the soil surrounding the piles (i.e., t-z and p-y curves as a function of depth along each pile and a q-z curve at the tip). Q-z curves at the tip are excluded for the drilled and grouted pile as per company guide lines.

The wave effect due to non-modeled items such as grating, handrails, anodes, clamps etc. are considered through hydrodynamic coefficient overrides. The appurtenances such as boat landing, riser protectors, conductor protectors, j-tubes, risers are considered as dummy members. These dummy members do not contribute to the global stiffness of the structure and attracts the wave force.

All the primary members of the jacket and deck are designated as plastic and secondary members are designated as elastic in the collapse input file to reduce the computing time.

2.2.2 Basis

The load-displacement relationship of a jacket structure is determined using large deflection, elasto-plastic, nonlinear, finite-element analysis. A full plastic collapse (pushover) analysis is performed to determine the load at which the structure collapses. Three levels of iteration are involved in the solution process. Any global load increment, a beam-column solution is performed for each plasticized member using the cross section sub-element details. The global stiffness iteration is then performed including the effects of joint flexibility, plasticity, failure and the foundation stiffness iteration including the nonlinear pile/soil effects.

For global solution process iteration, the deflected shape of the structure is determined and compared to the displacements of the previous solution iteration. If convergence is not attained, the new global displacements of the joints along with the beam internal and external loads are used to recalculate the elemental stiffness matrices. The structural stiffness iteration is then repeated including the effect of the foundation until the displacements meet the convergence tolerance.

2.2.3 Inelastic Non-linear Pushover Analysis

Static pushover analysis is the application of a single load, applied to any specific location which is incremented in steps until collapse. An inelastic static pushover analysis is carried out using the SACS “COLLAPSE” module. The SACS module “COLLAPSE” is a large deflection, elasto-plastic, nonlinear finite element analysis system for structures.

The SACS modules used for performing the pushover analysis are given below.

- SEASTATE: To generate environmental loads
- PSI: To perform non-linear foundation analysis
- COLLAPSE: To perform plastic non-linear pushover analysis
- COLLVUE: To perform interactive collapse results processor

Full lateral loading caused by 100 year return environmental storm is applied to the structure incrementally up to the collapse. The nodal displacements and element forces are calculated for each load step and the stiffness matrix is updated. The yield hinge formation is not the limit of the load-carrying capacity of structure and sufficient number of plastic hinges formed causing structural failure to form a kinematic mechanism. When the stress in the member reaches the yield stress, plasticity is introduced. The introduction of plasticity reduces the stiffness of the structure and additional loads due to subsequent load increments will be re-distributed to the adjacent members. This procedure (progressive collapse of the members) is continued until the structure, as a whole is collapsed or pushed over.

The factored gravity loads are applied first to the structure in one increment, thereafter the wave, current and wind corresponding to 100-year storm directional loading is applied to the structure incrementally through elastic and inelastic behavior until an ultimate condition of the structure is reached.

The analysis option includes joint flexibility, pile plasticity and member local buckling. The effect of strain hardening of 0.2% and fracture strain is included. The member calculated strain exceeded the fracture strain, the member will be removed from the stiffness calculation but it continued to attract hydrodynamic force.

The above procedure is adopted for all the critical directions with all the members' intact condition to determine the RSR of the platform.

The RSR is the load factor (L.F) applied to the full 100 year return design storm load prior to collapse or prior to obtaining maximum displacement. Overall RSR is the lowest RSR for all directions considered.

2.2.4 Material and Geometric Properties

Table 2.2.4.1 and Table-2.2.4.2 shows the material and geometric properties of the fixed offshore jacket platform respectively. Considering the increase in the load for the additional facilities for the extended life, the material yield strength is increased to an average of 15% based on the material test certificates as per the company guidelines. The member sizes selected are based on the all in-service and pre-service analyses of the offshore platform.

Table-2.2.4.1 Material Properties

Property	Value
Young's Modulus	20500 kN/cm²
Steel Density in air	7.85 MT/m³
Poisson Ratio	0.3
Shear Modulus	7890 kN/cm²
Yield Stress	34.5 kN/cm² for Thickness ≤40 mm 32.5 kN/cm² for 40<Thickness≤63mm

Table-2.2.4.2 Geometric Properties

Member	Diameter (mm)	Thickness(mm)
Jacket Legs (Vertical)	1439, 1419, 1389, 1369	60, 50, 35, 25
Jacket Horizontal and Diagonals	610, 508	30,20 25
Jacket Diagonals (Vertical Plane)	810, 762, 610	40, 38,30 25
J-Tubes	406.4	21.44
Piles	1219	50,40 and 32
Conductor	914 and 762	-
Deck Legs	914, 1067	32,38 45
Deck Plan Braces	219.1	12.7
Deck Vertical Braces	508, 406.4, 323.9, 219.1	16,20 12.7,25.4 12.7,15.88 12.7
Deck Primary Members	HEB 600, IPE 600,HEB 400	
Deck Secondary Members	IPE300, IPE240	

2.2.5 Loading

Loading on the offshore structure consists of gravity loads and environmental loads. Gravity loads are consists of dead weight structure, facilities of the platform permanent / temporary and live loads. Environmental loads play a vital importance in the design of offshore structure. Environmental data of the particular field is provided by the company. Various loads on the platform are given below.

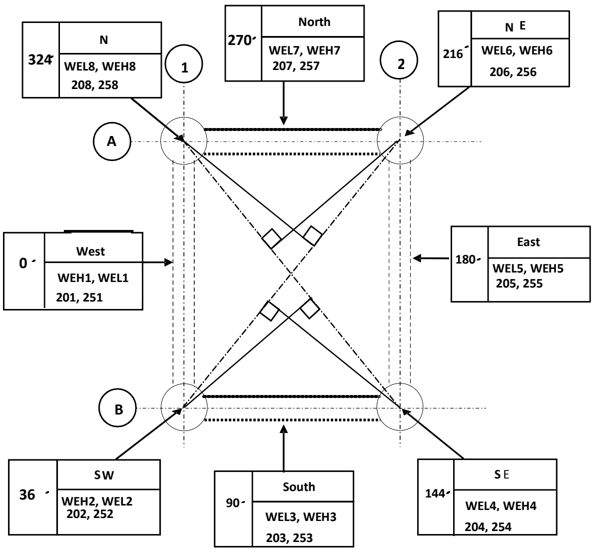
- Dead Load

  The total gravity load of the deck is 3243 MT including deck self-weight, live load, piping weight, equipment weights, electrical and instrumentation weight, architectural weight and HVAC weights.

  The total gravity load is increased by 50% for the expected increase in load due to additional facilities for the extended service life of the platform as per the company guidelines.

- Environmental Load

  Wave loads are generated based on stream function theory. The maximum uni-directional wave data, current data and wind data of the field is given table 2.2.5.1 are based on the Metocean data provided by the company. The environmental load cases and load directions for extreme storm condition are shown in figure 2.2.5.1.



Load Case: 201 to 208 and 251 to 258 – For 100 year extreme storm wave along with the current condition.
Load Case: WEL1 to WEL8 and WEH1 to WEH8– For 100 year extreme storm wind condition

Figure-2.2.5.1 Environmental Load cases and Directions

- Soil Data

Table-2.2.5.2 shows the soil stratigraphy till the end of bore hole depth. The complete geo-technical data for the drilled and grouted piles of the platform location is provided by the company and is not revealed in this paper.

- Load Combination

The extreme storm environmental load combination (wind, wave & current) considered for the pushover analysis is described below.

Load Combination for Minimum Water Depth: L000, L036, L090, L144, L180, L216, L270 and L324

Load Combination for Maximum Water Depth: H000, 036, H090, H144, H180, H216, H270 and H324.

The factored gravity loads are applied first to the structure in one increment, thereafter the wave, current and wind corresponding to 100-year storm directional loading is applied to the structure incrementally.

Table-2.2.5.1 Environmental Data for Platform Design

Direction (Degree)	Minimum Water Depth (100 year Return)		Maximum Water Depth (100 year Return)	
	Wave Height (m)	Wave Period (sec)	Wave Height (m)	Wave Period (sec)
0,36,90,144,180,216,270 and 324	8.0	8.2	8.1	8.3
Current Velocity in m/sec:				
Direction (Degree)	Surface	Mid depth	1m above Sea-bed	At seabed
0,36,90,144,180,216,270 and 324	0.87	0.68	0.37	0.37
Wind Speed:				
Directions (Degree)	100 Year Storm Wind 1 hour Mean			
0,36,90,144,180,216,270 and 324	21.8 m/sec			

Table-2.2.5.2 Soil Stratigraphy

Soil Layer below Seabed (m)	Soil Classification
0 - 2.3	Sandy Carbonate Silt
2.3 - 14.5	Weak to moderately weak weathered slightly siliceous calcaernite
14.5 – 55.6	Very week to weak slightly moderately weathered clacisiltite
55.6 -59.5	Very weak to weak slightly weathered calcerenite
59.5-70 (End of Bore Hole)	Very week to weak slightly moderately weathered clacisiltite

3. RESULTS AND DISCUSSIONS

The sea-state results for the 100 year extreme storm data with maximum and minimum water depth are given in table 3.1 below for identifying the critical load cases for performing the pushover analysis.

From the table-3.1, it is observed that H000, H036, H090, H180, H216, H270 and L324 are the critical directions based on the maximum lateral force on the platform for the pushover analysis.

The pushover analysis is performed for the structure intact conditions. The pushover analysis results with reserve strength ratios values are given table 3.2.

Table 3.1 Resultant Forces and Moments

Load Case		Dir.	Fx (MN)	Fy (MN)	Resultant Force (MN)	Mx (MN-m)	My (MN-m)	Resultant Moment (MN-m)
Minimum Water Depth	L000	0	6.2	-0.04	6.21	-3.70	137.1	137.2
	L036	36	4.6	2.96	5.49	-67.5	106.7	126.3
	L090	90	-0.02	4.17	4.17	-80.9	-0.784	80.91
	L144	144	-4.96	3.21	5.91	-68.3	-110.6	129.9
	L180	180	-6.26	0.032	6.26	-5.82	-133.2	133.3
	L216	216	-4.97	-3.19	5.91	68.4	-110.5	130.05
	L270	270	0.02	-4.74	4.74	85.09	4.142	85.19
	L324	324	5.21	-3.39	**6.22**	68.65	115.7	134.59
Maximum water Depth	**H000**	0	6.45	-0.03	**6.45**	-2.54	152.9	152.9
	H036	36	4.96	3.10	**5.85**	-69.8	118.8	137.8
	H090	90	-0.02	4.79	**4.79**	-92.79	-4.17	92.88
	H144	144	-5.10	3.25	**6.05**	-70.65	-120.1	139.3
	H180	180	-6.44	0.028	**6.44**	-5.41	-148.3	148.4
	H216	216	-5.08	-3.21	**6.01**	66.08	-116.4	133.8
	H270	270	0.014	-4.77	**4.77**	89.82	5.58	89.9
	H324	324	5.19	-3.29	6.15	65.46	125.2	141.3

Table-3.2 RSR for Different Load Sequences

Load Case	Base Shear at Design Load (MN)	Base Shear Before Collapse (MN)	RSR/LF	Remarks
H000	6.452	26.949	**4.2**	>1.45, Ok
H036	5.854	26.622	4.6	>1.45, Ok
H090	4.789	30.953	6.6	>1.45, Ok
H144	6.051	27.659	4.8	>1.45, Ok
H180	6.442	29.604	4.2	>1.45, Ok
H216	6.012	29.810	5.0	>1.45, Ok
H270	4.773	34.342	7.2	>1.45, Ok
L324	6.216	29.767	4.8	>1.45, Ok

The minimum reserve strength ratio (RSR) value is **4.20** from all the load sequences, which is higher than the required RSR of 1.45 as per the project guidelines of the platform.

The table 3.3 shows the pile capacity and total pile head load before collapse of the structure

Platform deformed shapes with PSI for different loading directions are shown in figure 3.1 and figure 3.2. Figure 3.1 shows the platform behavior at first hinge formation for different directional storm loads. From table 3.3 and figure 3.2, it is observed that the structural failures are caused not only by plasticity formation in the members but also pullout /punch thru due to insufficient bearing capacity of the soil for the increased load in excess of the design load.

Table 3.3 Pile Capacity and Pilehead Loads

Load Case	Pile capacity (MN)	Pile head load(MN)	Failure at Collapse
H000	58.13 (Tension)	1554.43 (Tension)	Pullout of Pile -A2 Grid Pile (Pile Capacity < Pilehead Load)
H036	58.13 (Tension)	32695.9 (Tension)	Pullout of Pile -A2 Grid Pile (Pile Capacity < Pilehead Load)
H090	56.86 (Comp)	42.85 (Comp)	Plastic Hinge formation on primary member causing excessive deflection (Pile Capacity > Pilehead Load A1 Grid Pile)
H144	58.13 (Tension)	20601.8 (Tension)	Pullout of Pile A1 Grid Pile (Pile Capacity < Pilehead Load)
H180	56.86 (Comp)	1124.1 (Comp)	Punch thru of Pile -A1 Grid Pile(Pile Capacity < Pilehead Load)
H216	58.13 (Tension)	1220.4 (Tension)	Pullout of Pile (003P)- B1 Grid Pile (Pile Capacity < Pilehead Load)
H270	51.56 (Comp)	34.31 (Comp)	Primary Joint Failure. (Pile Capacity > Pilehead Load B2 Grid Pile)
L324	58.13 (Tension)	16953.2 (Tension)	Pullout of Pile (002P) - A2 Grid Pile (Pile Capacity < Pilehead Load)

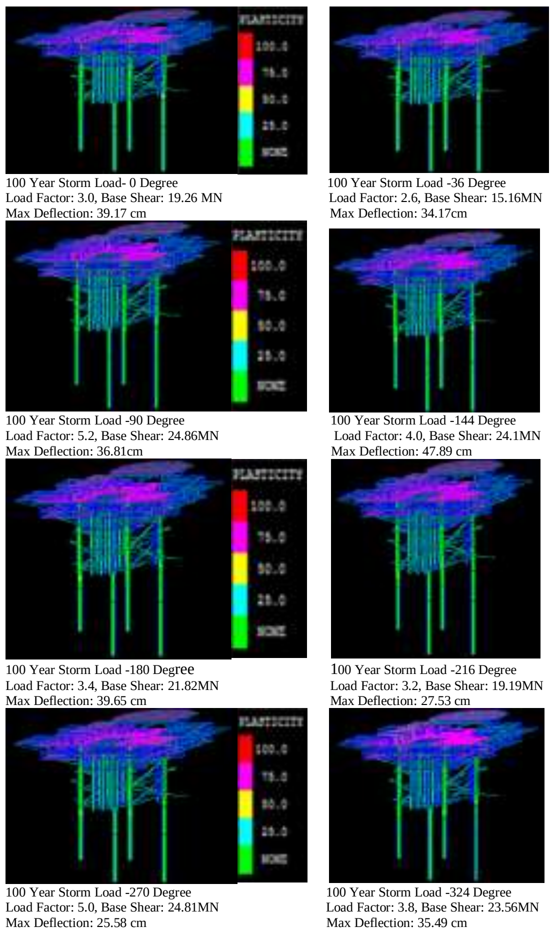


Figure 3.1 Deformed shape of the Platform at First Hinge Formation for Directional 100 Year Storm Load

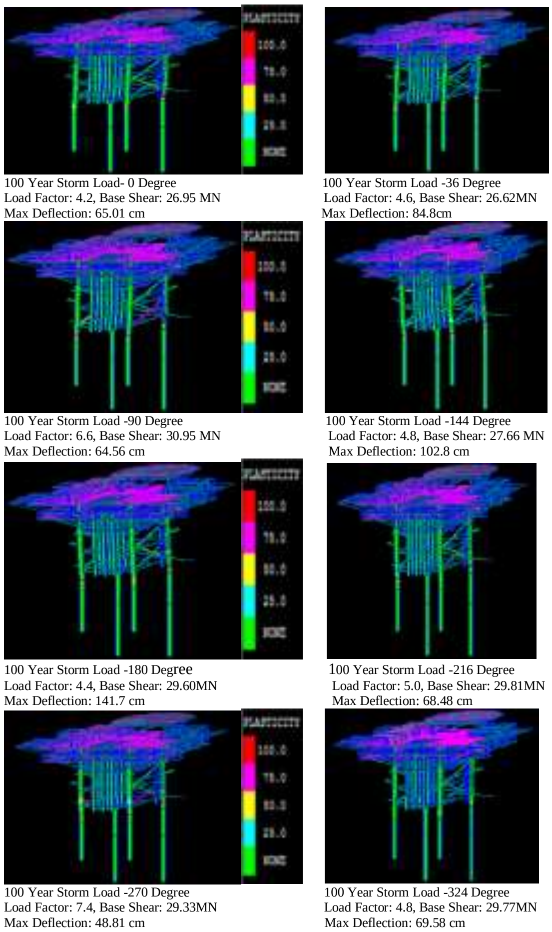


Figure 3.2 Deformed shape of the Prior to Collapse due to Directional 100 Year Storm Load

The figure 3.3 shows the trend of reserve strength ratios of the platform with respect to the directional 100 year storm load.

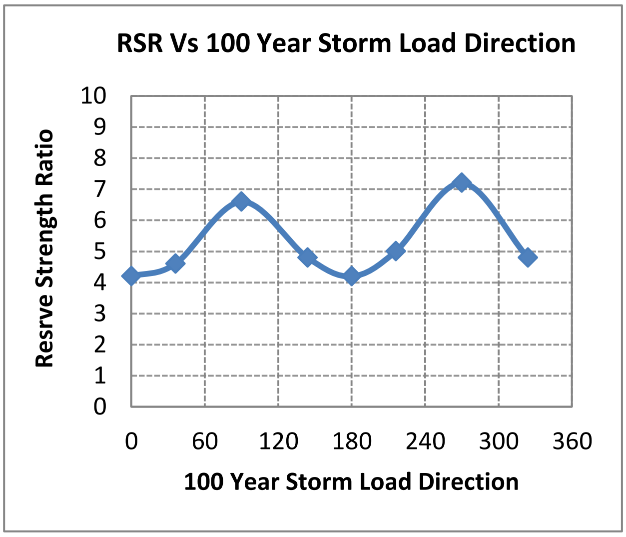


Figure-3.3 RSR Vs 100 Year Storm Load Direction

4. CONCLUSIONS

- The pushover analysis of the fixed offshore jacket type wellhead platform structure with drilled and grouted steel piles shows that it possesses strength in excess of the original design gravity and environmental loads.
- First hinge is not the limit of the load-carrying capacity of the platform and structural failure is indicated once a sufficient number of plastic hinges have formed to make a kinematic mechanism.
- Pile failure indicated is not only by plastic hinge formation but also through pile punch thru/ pullout due to inadequate soil capacity for the incremental load in excess of the design load.

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