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Seismic Time History Response of the Maleo Producer

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Abstract

The Maleo Producer is a converted Bethlehem JU 250 (1970’s design) mat-supported jack-up that is currently operating as a gas production platform in the Madura Straits, offshore Indonesia. The field is located in a seismically active region. This paper summarizes the procedures used to assess the structural adequacy of the platform for seismic loading. The reported results along with those for overall foundation stability were accepted by the American Bureau of Shipping for class approval of the structure as a fixed offshore installation.

Introduction

The Maleo Producer is a Bethlehem JU250 (1970’s vintage) mat supported jack up that was converted to a gas production platform for operation in the Madura Straits offshore northern Indonesia. The site design water depth is 187 ft. This mode of operation is a significant departure from its original design as a mobile offshore drilling unit (MODU). The conversion technically defines the platform as a mobile offshore production unit (MOPU), however the platform will operate on location for a period of 14 years. Consequently, the unit was classed as a fixed offshore structure. Class was sought with the American Bureau of Shipping using the requisite class documents (ABS, 1997). The procedures of API RP 2A (API, 2000) were used to define the seismic analysis methodology and determine structural response for seismic loads.

The class process required confirmation of platform adequacy for storm and fatigue loading. These loading conditions were part of the original platform design basis and hence the structural performance, with minor modifications to account for ageing, was readily demonstrated. Seismic loading was not part of the original design basis of the structure and thus required rigorous investigation to confirm adequacy in terms of strength, ductility, and overall stability. The issue of overall stability was further compounded by the site soil conditions which were relatively soft (Neubecker and Audibert, 2008 and Spikula and Garmon, 2008). Demonstration of overall stability of the platform was carried out by a combination of analytical methods (Murff and Young, 2008) and three dimensional soil structure interaction analyses (Templeton, 2008). Results from the soil structure interaction analyses formed the input loading to the structural time history analyses and the study of load transfer thought the pins that support the deck.

Background

Platform Structural Details

The Maleo Producer is a self elevating unit that employs two sets of six pins (per leg) and hydraulic rams (two per leg) as a jacking mechanism. Pin sets are alternatively engaged and rams extended or contracted to raise and lower the deck. The platform was originally designated as the Cliffs Drilling Number 10 (CD10) which operated in early years in the Gulf of Mexico and laterally as a Mobile Offshore Production Unit (MOPU) in the Arabian Gulf. Conversion of the platform for gas production was carried out in Sharjah in 2005-2006. The conversion included a complete refurbishment of the deck and addition of new process equipment, addition of a flare tower, reduction in leg length from 312 ft to 282.25 ft, modification to the leg and mat connection for improved fatigue performance and the addition of sponson tanks to improve afloat stability during installation. Details for the platform configuration in production mode with deck elevated are given in Table 1.

Structural Component	Weight (kip)	LCG (ft)	TCG (ft)	VCG (ft)
Mat Steel plus Ballast	11872	-96.46	0.00	4.75
New Stability Tanks	222	-105.00	0.00	21.00
Mat Steel + Ballast + Stability Tanks	12094	-96.62	0.00	5.05
Cut Columns (3)	2438	-93.34	0.00	134.99
New Steel at Mat Column Connection	71	-63.28	0.00	7.12
Deck Outfitted no Fluids	7748	-97.35	-1.57	270.33
Lightship No fluids	**22351**	**-96.41**	**-0.54**	**111.19**
Target from Inclining Test	22336	-96.48	-0.55	111.25
Difference	15	0.1	0.0	-0.1
	0.07%	-0.07%	-0.37%	-0.05%

Table 1: Maleo Producer Details (Elevated Condition)

Following conversion, the platform was dry towed from the Arabian Gulf to its operating location offshore Indonesia (Figure 1).

Figure 1: Maleo Producer Madura Straits, Indonesia

The site water depth in conjunction with air gap requirements, potential field subsidence and short and long term consolidation of the foundation placed the deck at an elevation of 239 ft. This pin holes at this elevation did not have supporting bearing plates.

Storm and Fatigue Performance

Structural analysis of the platform was carried out using ABAQUS (Dassault Systèmes, 2007). A detailed platform model was constructed in order that potential structural modifications could be easily incorporated and load paths could be traced through the mat structure, the mat-to-leg interface and the jackhouse and pin-to-leg connections (Figure 2). Lateral load transfer between the deck and legs (through guide frames at the top and bottom of each jackhouse) was represented by nodal constraint equations. Pin-to-leg connections were idealized in a way that gapping could be included or omitted without major modification to the model. This allowed the same analysis model to be used for extreme loading, fatigue analysis and the initial stages of the seismic analysis. Discussions with the class society resulted in only the load path through the lower or fixed pins being represented in the model. This approach was adopted because the load transfer path through the upper pins relied on the supporting hydraulic rams remaining pressurized throughout the operational life of the platform.

Beam elements were used to represent the majority of the legs. Leg properties accounted for the variation in wall thickness and additional nonstructural mass due to internals such as ring stiffeners. The bottom 40 ft of the legs were represented by shell elements that were integral with the mat idealization. Connectivity between the beams and shell was made with nodal constraints.

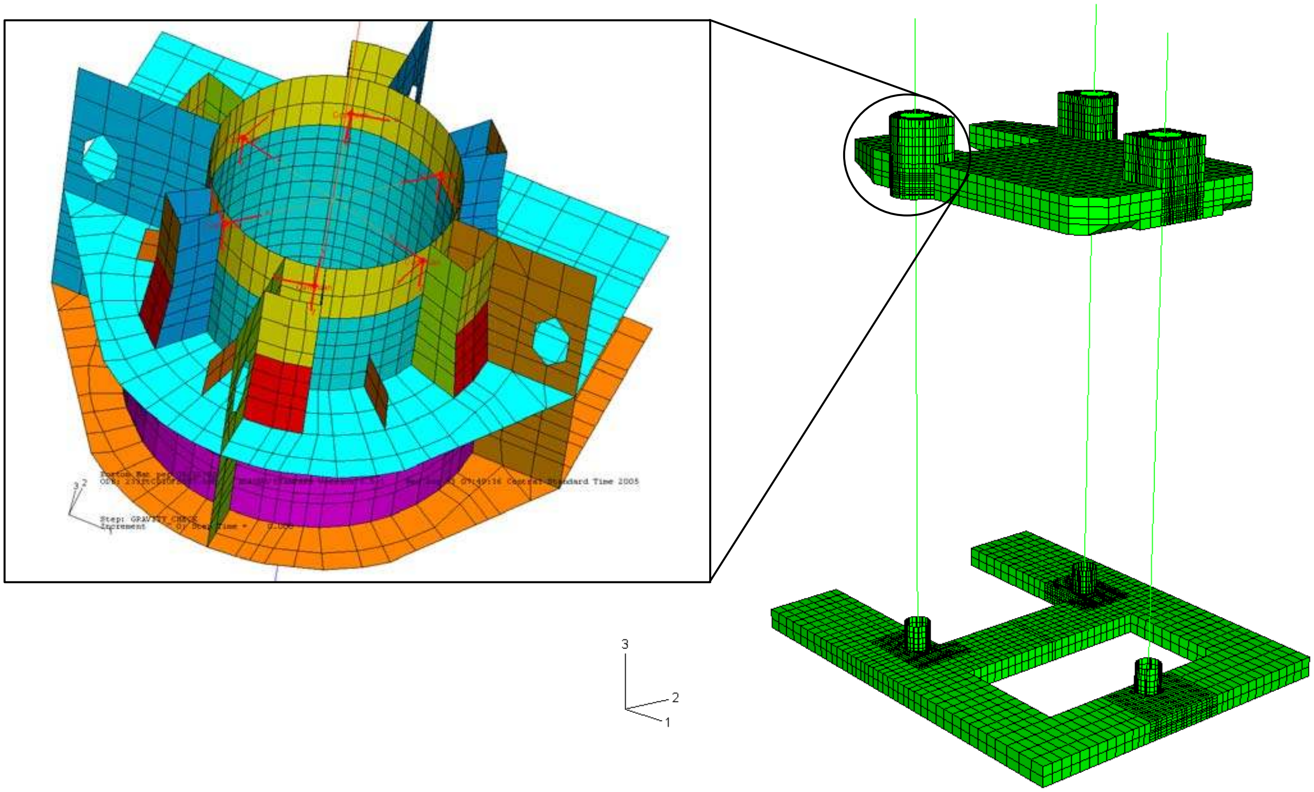

Figure 2: Detailed Structural Model of Maleo Producer

The platform model was founded on an array of springs (one of each node on the base of the mat). Local spring properties were based on the tributary area of shell elements such that the total foundation response was consistent with soil springs derived from site data. Three sets of soil springs were used to account for translation in the horizontal and vertical directions.

Design metocean conditions for the Maleo Field are relatively benign (Table 2). Adequate structural performance was readily demonstrated with relatively low leg utilization factors at the critical locations below the lower deck guides and at the mat-to-leg connection. The addition of new process equipment to the topsides increased wind loading which resulted in an increase in overturning moment. Demonstration of adequacy for stability in overturning was carried out using analytical methods. (Murff and Young, 2008). Pin loads were assessed to determine the bearing capacity of the local leg material. This was found to be marginal.

Definition	1 Year – Operating Conditions	100 Year– Extreme Conditions
Water Depth (MSL) (ft)	187.00	
LAT (MSL) (ft)	-4.53	
HAT(MSL) (ft)	4.23	
MHWS (MSL) (ft)	3.44	
Storm Surge (ft)	0.10	0.43
H_{max}, (ft)	19.13	30.64
T_p, (sec)	11.71	14.90

Table 2: Extreme Operating Conditions for the Maleo Field

The site fatigue environment is highly directional with a dominant westerly heading. Fatigue performance was demonstrated for the legs and pin holes remote from the mat-to-leg connections. Operation of similar mat supported MODU's has shown that the mat-to-leg connection is a fatigue sensitive area. Historical records for the Maleo Producer indicated that usage was typically in shallow water and that the platform had been mothballed for a significant portion of its life. Nonetheless, additional gussets plates were included and internal bulkheads were replaced such that load transfer was redistributed away from the original connection details (Figure 3).

Figure 3: Retrofitted Mat-Leg Connection (At Top of Mat)

Seismic Demand

A site specific seismic hazard study was conducted for the Maleo Field (Nisar, 2008). Results from the seismic hazard study were a series of ground motion spectra (Table 3). Three sets of time histories were developed for surface ground motion using actual recorded earthquake histories as seed motions. They were defined as events one, two and three, respectively.

Return periods for the strength Level (SLE) and Ductility Level (DLE) events were selected in discussion with the platform operators. These were chosen to be 200 years and 1000 year, respectively. Further assessment was also carried out to demonstrate adequate performance for a ductility level seismic demand consistent with a return period of 5000 years.

Coefficients	**Return Period (Years)**					
	100	**200**	**500**	**1000**	**2000**	**5000**
PGA	0.10	0.15	0.24	0.33	0.45	0.65
S_{a1} (g)	0.16	0.23	0.34	0.49	0.67	0.93
S_{a2} (g)	0.14	0.20	0.34	0.49	0.67	0.99
T_1	0.10	0.10	0.10	0.10	0.10	0.10
T_2	0.875	0.870	1.000	1.000	1.000	1.065
T_3	4.0	4.0	4.0	4.0	4.0	4.0

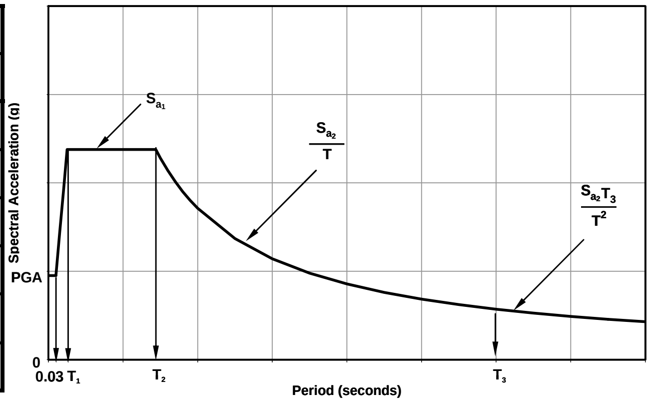

Table 3: Site Specific Ground Motion (Mudline)

Response Spectrum and Pushover Analyses

Response spectrum calculations were performed prior to time history analysis as a means of investigating structural response. For this set of analyses, the detailed platform model was linearized (no uplift was permitted at the pins).

Modal analysis of the platform was carried for both SLE and DLE events. Degraded soil springs were used as a means of accounting for energy dissipation in the soil. This was known to be a crude approximation and was intended to be indicative only. Modal response in the SLE event indicated a first sway lateral period (on soil springs) was of the order of 4.4 seconds (in both horizontal directions). The second significant lateral mode was consistent with mat excitation and was of the order of 0.7 seconds. The first and second significant lateral modes accounted for over 95% of the structural mass of the platform. Vertical response was dominated by a single mode with a period of the order of 0.7 seconds. This accounted for over 90% of structural mass in the vertical direction. It was noted that the second lateral period was close to the peak of the input spectrum (Figure 4). This implied that the mat mass would be the dominant contributor to base shear.

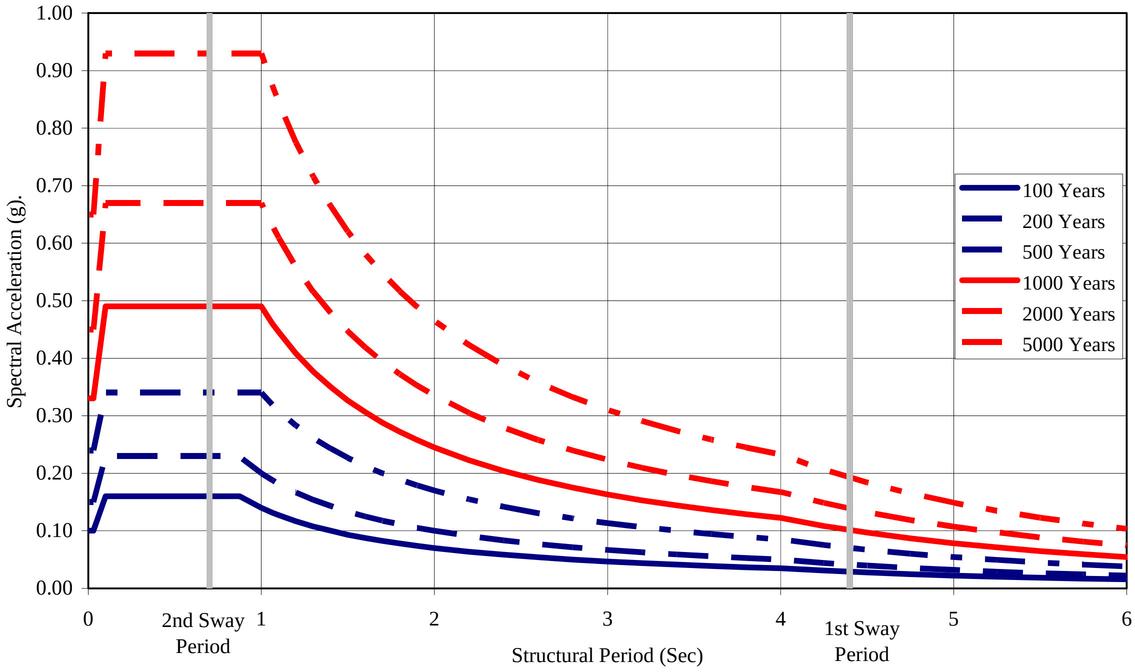

Figure 4: Comparison of Lateral Periods of Response and Input Ground Motion

Base shear demand from the response spectrum analyses for the SLE load level indicated that the slippage of the platform was likely. Pushover analyses for the SLE demand level were also carried out to assess the potential for pin uplift. This indicated that pin uplift was unlikely. Leg member checks and assessment in the overall stress distribution in the mat showed that all remained at moderately low levels of load.

Pushover analyses for the DLE loading level indicated that pin uplift could be anticipated. Peak pin loads were used to assess bearing loads at the pin leg interfaces. These were found exceed local bearing capacity of the legs. Member checks were also performed for the DLE load level. These indicated that member utilization still remained at a moderate level. This approach was taken as there are no redundant structural load paths between the platform legs. The overall stress distribution in the mat indicated that post yield response was limited to very small areas on the gusset plates that were added to improve fatigue performance.

General trends on structural performance were clear from the response spectrum and pushover analyses. Results were, however, limited due to the expected foundation response, the potential for slippage and the potential for pin uplift. In addition, the limitation in calculation procedures associated with overall stability meant that adequate stability could not be conclusively demonstrated. While the response spectrum method indicated that mat slippage was possible in a seismic event, a reliable means to assess the magnitude of slippage could not be readily demonstrated to the satisfaction of the class society. Not withstanding these limitations, the following conclusions could be drawn from the response spectrum analysis:

- At the strength level earthquake event, pin uplift is unlikely from the combination of deck sway and vertical loads. However, platform slippage is likely.

- At the upper level earthquake loading, pin uplift is likely and local bearing stress levels could potentially exceed material allowables in the legs. Platform slippage was more than likely.

Remedial action was taken to address the pin bearing loads by the retrofit of steel doubler plates (Figure 5). These were placed on all pin holes where a pin was located when the platform was in its elevated position.

The limitations on reliably assessing pin uplift, platform slippage and overall stability on the foundation meant that further seismic assessment had to be conducted in the time domain.

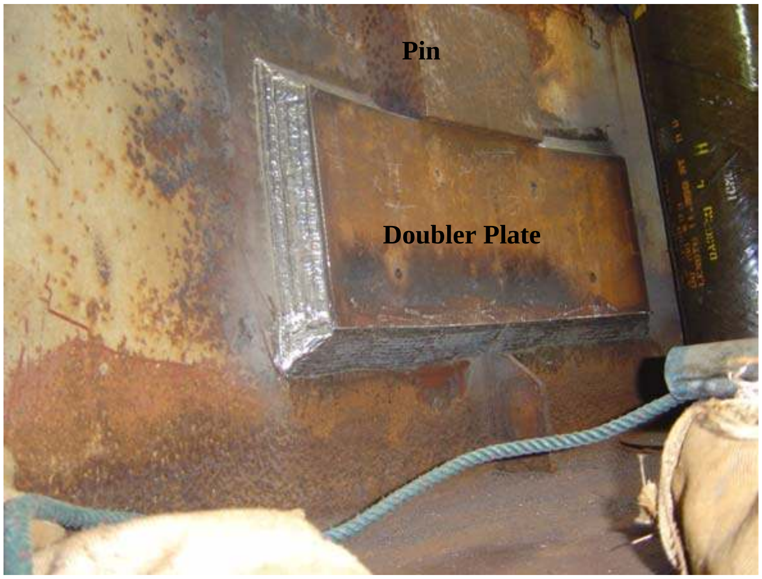

Figure 5: Additional Doubler Plates to Increase Bearing Capacity (12 Locations per Leg).

Time History Analysis Procedure

A fully coupled soil structure interaction analyses was required to assess overall stability of the Maleo Producer (Templeton, 2008). This approach required an explicit representation of the soil mass below the mat which extended outwards for a sufficient radial distance to prevent boundary effects polluting the results of interest (Figure 6). Time history analyses with this model required significant computational effort. Model development indicated that local mat and deck flexibility and pin gapping did not significantly affect global base shear and overturning moments. Pin gapping was, however, found to significantly reduce solution time step with an associated increase in overall run time.

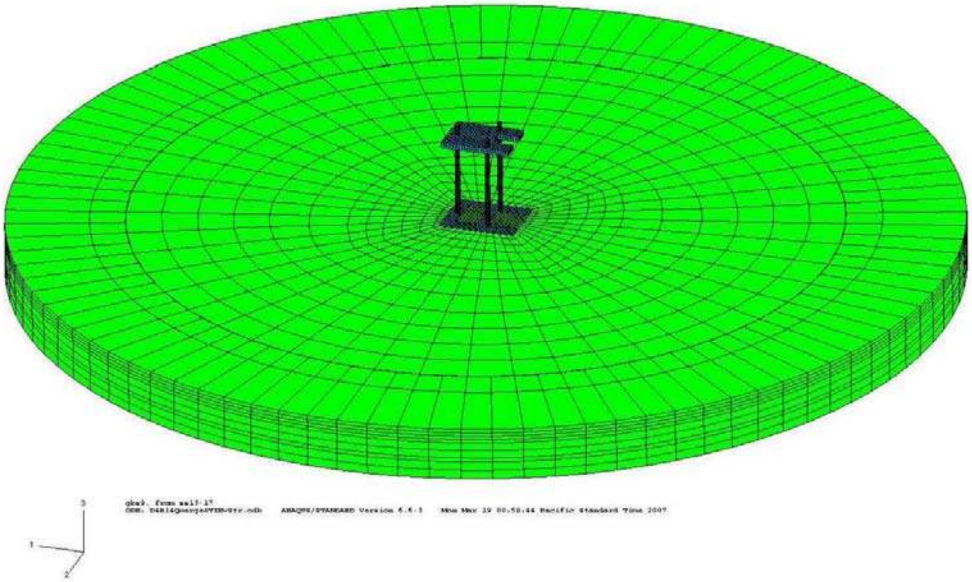

Figure 6: Global Soil "Island" Model for Soil Structure Interaction Analyses

Time history analysis of the platform was therefore decoupled into two parts. Both utilized a platform model where the leg idealization from the storm and fatigue model was retained and the mat and deck were represented by mass and inertia elements (Figure 7). The mass and inertia characteristics of the mat and deck were derived from the detailed structural model. Nodal constraints were used to tie the base of each leg to the mass node representing the mat. The deck was constrained laterally to the legs at the upper and lower guides while vertical load was transferred through the pins.

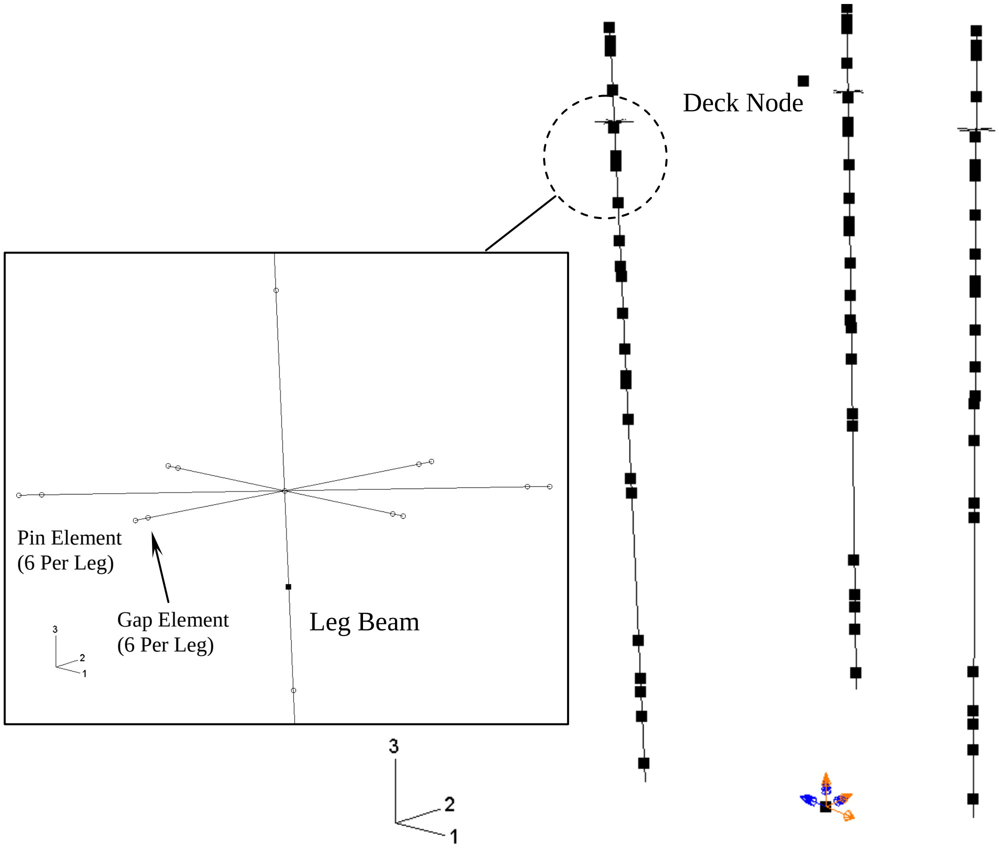

Figure 7: Structural Model for Seismic Time History Analysis

The global soil structure interaction model considered the leg pin connection as constrained and focused solely on overturning and mat slippage under seismic loads. Structural analysis of the platform included pin gapping and focused on the local effects of pin uplift. Input to the structural model consisted of motion time histories from the mat that were derived in the soil structure interaction analysis.

Comparative runs between model configurations that included or omitted pin gapping showed the deck motions to be very similar verifying the assumption that local pin effects did not significantly affect platform global response.

Mat motions were applied to the mat of the structural model in all six degrees of freedom after an initial load step to initiate self weight and buoyancy. This was repeated for each set of input time histories for the ductility level earthquake. An additional set of runs were performed for motions when the input motions (to the soil structure interaction model) were doubled. This was representative of an earthquake with return period of approximately 5000 years. Nonlinear geometry (P-Δ effect) was included in all analyses.

Structural Response – Ductility Level Earthquake

A typical set of pin loading time histories at the forward leg are shown in Figure 7. While intermittent uplift was observed at some pin locations, there was no case where all pins simultaneously unloaded. Scaling the input motion by a factor of two significantly increased the duration of uplift for individual pins but again, all pins did not uplift at one time.

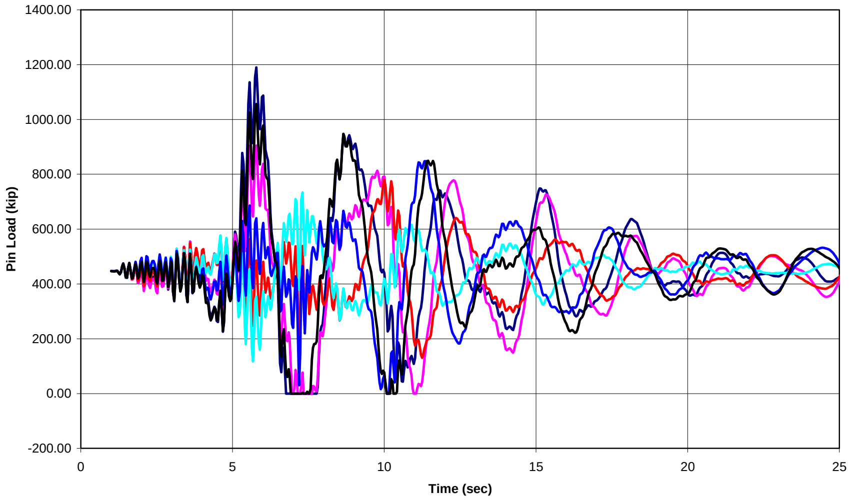

Figure 7a: Pin Force Time Histories (Fwd Jackhouse) - Event 1 Motion (Negative Denotes Uplift)

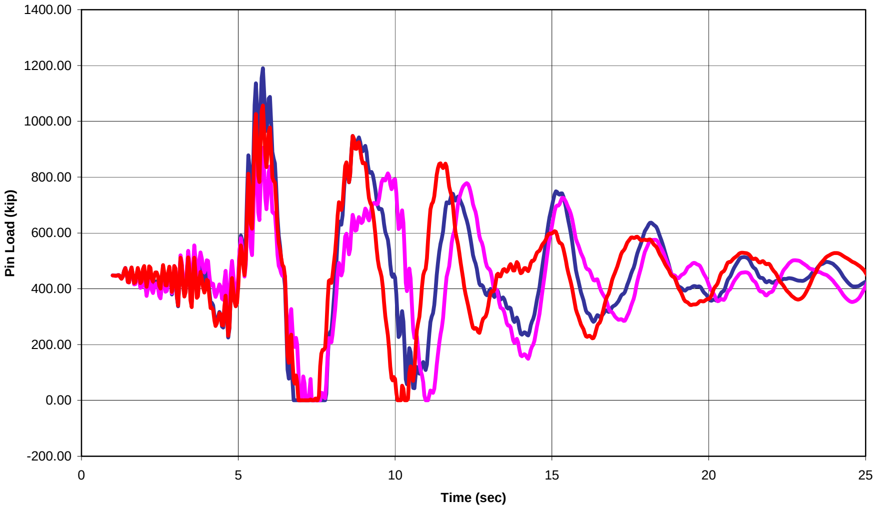

Figure 7b: Pin Force Time Histories with Uplift (Fwd Jackhouse) - Event 1 Motion (Negative Denotes Uplift)

Stress time histories from each leg elevation were used to calculate member utilization factors. Peak values are reported in Table 4. In all cases the maximum utilization occurred approximately 10 ft below the deck and was consistent with the leg elevation where the leg wall thickness reduced. Utilization factors remain below one, even when the DLE input motion was scaled by a factor of two.

Leg	Unscaled Input Motion			Scaled Input Motion		
	Event 1	Event 2	Event 3	Event 1	Event 2	Event 3
Forward	0.58	0.55	0.55	0.86	0.82	0.98
Aft Port	0.58	0.55	0.63	0.87	0.85	0.97
Aft Stbd	0.56	0.65	0.55	0.90	0.90	0.90

Table 4: Peak Leg Utilization (DLE Event)

The recorded peak instantaneous bearing stresses at each pin were all lower than elastic bearing limit of the leg and doubler plate material. This was the case for all three design motions. In addition, bearing stresses were of the order of 60% of those estimated by the response spectrum and pushover method. Bearing stresses marginally exceeded yield at a number of pin locations when the design input motions were doubled.

The low level of bearing stresses and leg utilization factors for the design input motions and the relatively good performance of the structure when motions input were scaled by a factor of two provided confidence in the structural robustness of the platform under seismic loads.

Conclusions

Use of a mat supported MOPU as a fixed offshore structure in seismically active regions requires that specific attention be paid to seismic loading. Global effects such as overturning and mat slippage are of particular concern when the platform is located on a soft soil site. Structural adequacy with respect to the leg members, the potential for pin uplift and local pin bearing loads must also be confirmed as adequate. All of these aspects of structural response can be addressed directly through platform nonlinear time history analyses with soil structure interaction effects and structural and geometric nonlinearity.

A series of nonlinear time history analyses were performed for the Maleo Producer to assess soil structure interaction effects and the potential for overturning and mat slippage. Input to the analyses took the form of a series of time histories of earthquake motions that were representative of a ductility level event. Results from these analyses were used to drive the structure model to assess pin uplift, local bearing loads and leg member adequacy. Leg member loads developed member utilizations below unity. Adequate member response was also obtained when the input motions were scaled to be representative of a more extreme event with a return period of 5000 year. Pin loads and bearing stresses all remained in the elastic range at the demand ductility event level.

The reported results along with those for overall foundation stability were accepted by the American Bureau of Shipping as sufficient justification to give class approval of the Maleo Producer for operation as a fixed offshore structure.

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