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The Maleo MOPU Project—Project Overview and Keynote Address

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Abstract

The Maleo Producer is a Mobile Offshore Production Unit (MOPU) that is owned and operated by Global Process Systems (GPS). The MOPU is currently leased to Santos and operates offshore Indonesia. First gas was produced in September 2006. This overview paper describes the conversion, operations and benefits that can be recovered through a MOPU deployment.

Safely designing a relatively old mat-supported jack-up drilling structure, to operate as a MOPU on a very soft soil, in a very seismically active location, was challenging. Technical efforts were placed on the dynamic analysis of the foundation coupled with the structure. The circumstances required unusually advanced analytical efforts in the fields of geotechnical and structural engineering. ABS, the selected classification society, needed special assistance in understanding the soils issues, especially in terms of the structure's response to seismic events.

Site investigations were performed both before and after the structure was placed on location. Extensive in-situ measurements of the soil characteristics in the mat-effected zone were made after the structure was installed. Advanced static and dynamic laboratory tests of the soil were undertaken. A new method of computing the overturning resistance of typical mat foundations on soft soils was developed. A very large 3-D non-linear dynamic finite element soil island foundation model was developed and linked with the structural finite element model. A site-specific seismic hazard study produced time series data for ground motions for design verification and dynamic response predictions.

This paper provides an overview of the last and most difficult phase of the Maleo project and explains how each of the following six papers in this session relates to the project and to each other. The culmination of this last phase was full class approval being given to the Maleo Producer as a fixed offshore structure.

Introduction

Shallow water marginal field development demands a cost effective solution with expedient delivery and commissioning of production assets in order that field development plans and concession development obligations are met. Field development is further complicated by uncertainty of reservoir life; a leased facility mitigates the reservoir risks by offering flexible lease terms and limits capital expenditure by the field operator while reservoir performance is evaluated. Conversion of a 250 ft class MODU such as a the Maleo Producer for MOPU applications readily meets these requirements with a fast conversion project timetable as opposed to conventional new build, simple installation procedure, easy relocation of the unit during the field operational life cycle and minimal abandonment costs.

The Maleo Producer (Figure 1) is an example of a Mobile Offshore Production Unit (MOPU) that provided cost effective exploitation of a marginal field. The platform is currently leased to Santos and operates offshore Indonesia in a water depth of 187 ft (Figure 2). First gas was produced in September 2006.

The Maleo site is underlain by very soft normally consolidated highly plastic lightweight marine clay. Site conditions were evaluated in a typical geotechnical investigation, which developed material parameters for the clay in terms of typical geotechnical variables (PT Kalindo Raya Semesta, 2003). Site soil conditions and their characterization contributed greatly to the challenges of this project.

While the MOPU is not a new concept, each individual project has its own unique project and technical challenges. This paper covers in detail some of the challenges faced during the Maleo project execution and the expertise and innovative technology that was employed to overcome them.

Figure 1: The Maleo Producer – On Location in 187 ft Water Depth, Offshore Indonesia

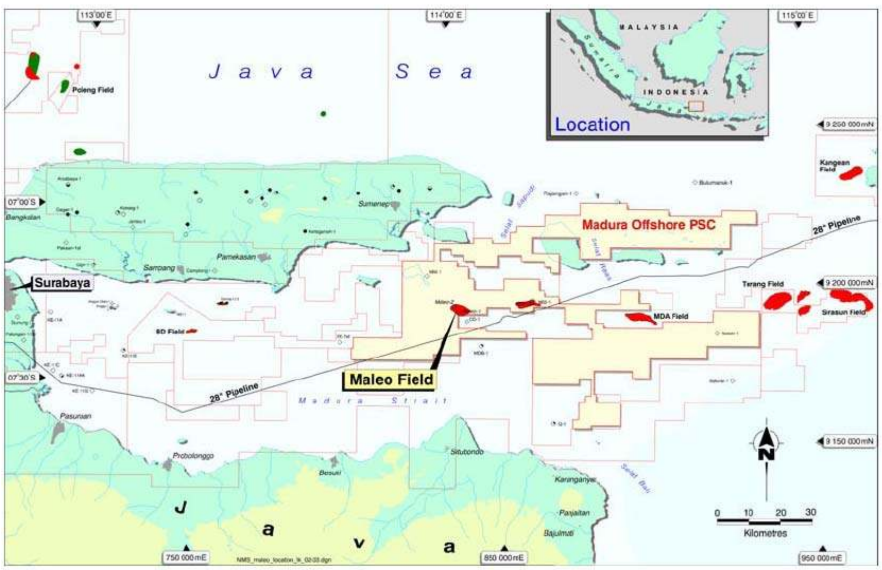

Figure 2: Maleo Field Location

Project Drivers and Challenges

The primary drivers for the Maleo Project can be best described under two categories - cost and delivery. These are common to any offshore project in the petroleum industry. The Maleo Project was delivered from formal project kick off to production in 16 months. The use of mat supported MODUs converted to production units provides the template to deliver the structures on a fast track basis, as opposed to conventional new-build fixed structures, or MOPUs, which currently have an approximate delivery schedule of two years, if fabrication capacity is available.

The challenge for this type of project is not now so much economic feasibility but the technical aspects of converting a mobile unit to a site specific fixed structure under a specific class notation. The requirements for the site specific structure are location dependent and may include environmental conditions that the original MODU structure was not intended to operate in. This challenge was presented at the Maleo field location where and seismic design considerations in conjunction with the soft clay site needed to be taken into account in qualifying the unit for its operational life.

The execution of projects of this nature requires a close working relationship between all parties from client through to all of the respective contactor, classification societies and engineers of many disciplines. The Maleo project and in particular the structural and geotechnical team put together by Stewart Technology Associates (STA) is the most prominent example of the expertise, coordination and effort that is required by a project of this nature.

Maleo MOPU Description

The platform is a Bethlehem JU250 (1970's vintage) mat supported mobile offshore drilling unit (MODU) that was designated as the Cliffs Drilling Number 10 (CD10) and was originally classed as a MODU by the American Bureau of Shipping (Hull Class Number 7900120). The Maleo Producer and its sister vessel the Cendor MOPU (formerly the Odin Liberty) and are both currently operating on a lease basis in South East Asia. The process scheme on the Maleo Producer is a 120 MMscf/d gas dehydration and compression facility delivering gas to the Indonesian natural gas network.

Although the conversion is technically defined as a mobile offshore production unit (MOPU), the platform may 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 (ABS) using the requisite class documents (ABS, 1997).

The platform consists of an "A shaped" mat with nominal dimensions of 210 ft by 170 ft by 10 ft (Figure 3). The mat has an internal slot with dimensions of 59 ft by 108 ft and an external slot to the aft that is 87 ft by 90 ft. The bottom of the mat has a 2 ft skirt that extends around its outer perimeter and the perimeter of the slots. The skirt also extends across the bottom of the mat in several locations. Internally, the mat is stiffened by a series of watertight and non watertight bulkheads. The watertight bulkheads form a series of buoyant tanks that are distributed throughout the mat. The mat bearing area (excluding cut-outs) is 21616 ft^2 (2008 m^2). The rectangular mat area, including cut outs is 35700 ft^2 (3317 m^2). The ratio of these areas is 1:1.65.

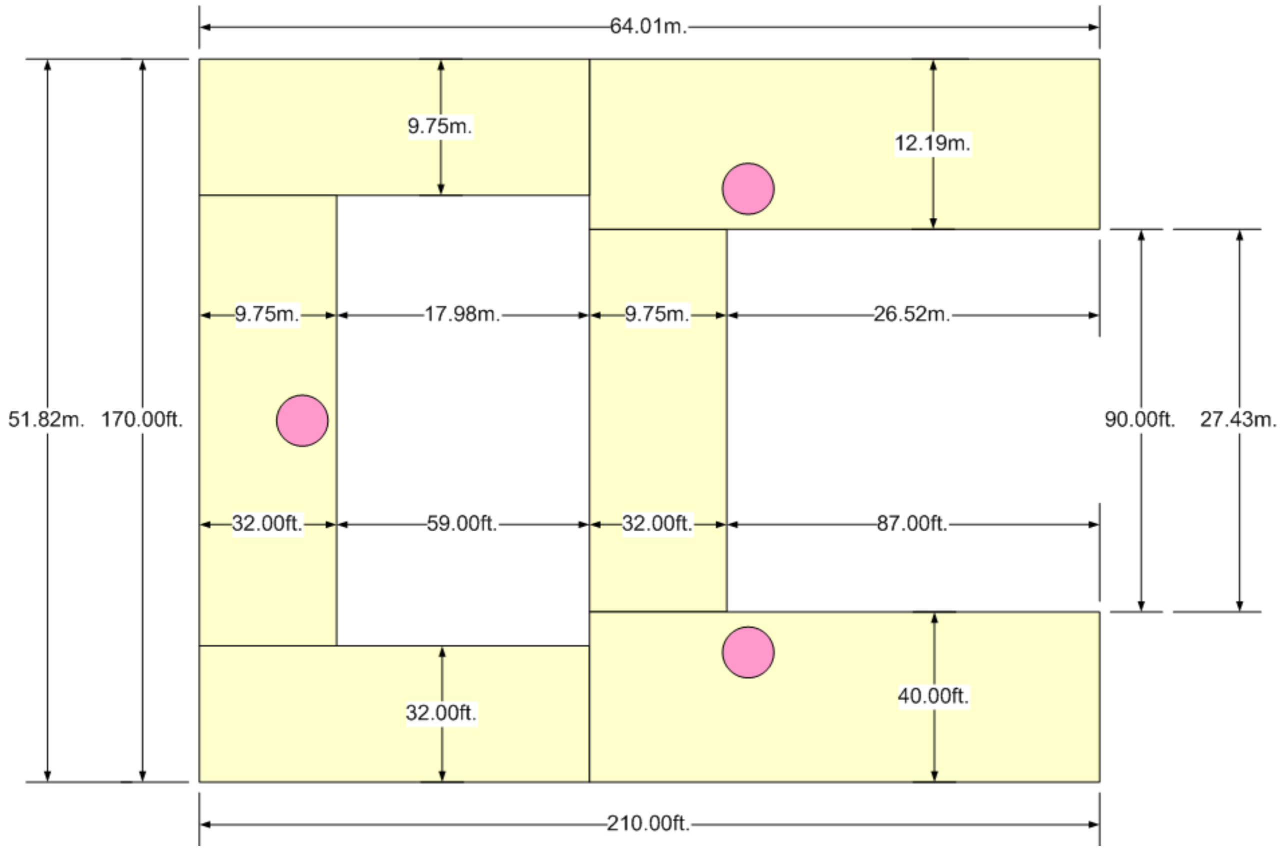

Figure 3: Mat Dimensions and Leg Locations

The platform deck is supported by three legs with outside diameter of 12 ft and variable thickness (ranging from *2.25* inches to *1.75* inches). The original leg length was 312 ft from the bottom of the mat. Pin holes are located every 12 ft for the deck jacking mechanism. The legs are flooded during operation. Internals to the legs consist of ring stiffeners, construction spiders and doubler plates over the majority of the leg length to support the jacking pins.

The nominal deck dimensions are 176 ft by 132 ft with a nominal depth of 14 ft. The deck is self elevating with two sets of six pins (per leg) and a jacking yoke on hydraulic rams (two per leg) comprising the major components of the jacking mechanism. All deck vertical loads are transmitted to the legs through the large rectangular steel pins. Pin sets are alternatively engaged and the ram extended or contracted to raise and lower the deck. The pins and hydraulic rams are located in three jack houses.

Prior to conversion, the CD10 operated as a MOPU in the Arabian Gulf. Deck process equipment was relatively light and the platform operated in benign conditions.

Platform Modifications and their Impact on Installation

Conversion of the CD10 to the Maleo Producer was carried out in Sharjah and Dubai between Q2 of 2005 and Q2 of 2006. The conversion process consisted of a complete refurbishment of the structure, reduction in leg length from 312 ft to 282.25 ft, installation of a flare tower and installation of the gas dehydration and compression facilities. The new topside facilities represented a significant increase in deck loading resulting in an increase in the deck center of gravity (VCG) from original design.

A series of gusset plates (eight per leg) were added at the connection of the legs to the top plate of the mat. These provide an alternate load path and protect the fatigue sensitive wrapper plate connection from the original design. This approach was taken as past fatigue life from the 30 years of operation could not readily be quantified. Each gusset plate was located on a bulkhead and the bulkhead steel was also replaced such that the gusset web and bulkhead were formed from continuous steel plate. New deck plate was also provided around the gusset plates.

The gusset plates extended 6 ft above the top of the mat which limited the lowest deck position relative to the mat. This did not present a problem for in-place operations. However, the relatively higher deck elevation in combination with the increased deck loading limited the afloat stability of the platform. This was mitigated by the addition of four large open-topped sponson tanks that were located at each corner of the mat (Figure 5).

Figure 5: Mat Sponson Tanks and Gussets at Mat to Leg Connection

The design water depth for the platform is 187 ft. The design deck elevation was set at 239 ft to account for, initial mat penetration on installation, short and long term settlement, potential subsidence as the field is depleted and environmental conditions. This deck elevation was at a height where the pin holes were not supported by doubler plates. New doubler plates were added at these locations and the new plates were sized using seismic demand loads (Figure 6).

Table 1 shows the weight summary of the platform after conversion.

Structural Component	Weight (kip)
Mat steel + ballast + sponson tanks	12094
Cut Columns (3)	2438
New steel at mat column connection	71
Deck outfitted no fluids	7748
Lightship No fluids	**22351**

Table 1: Platform Characteristics

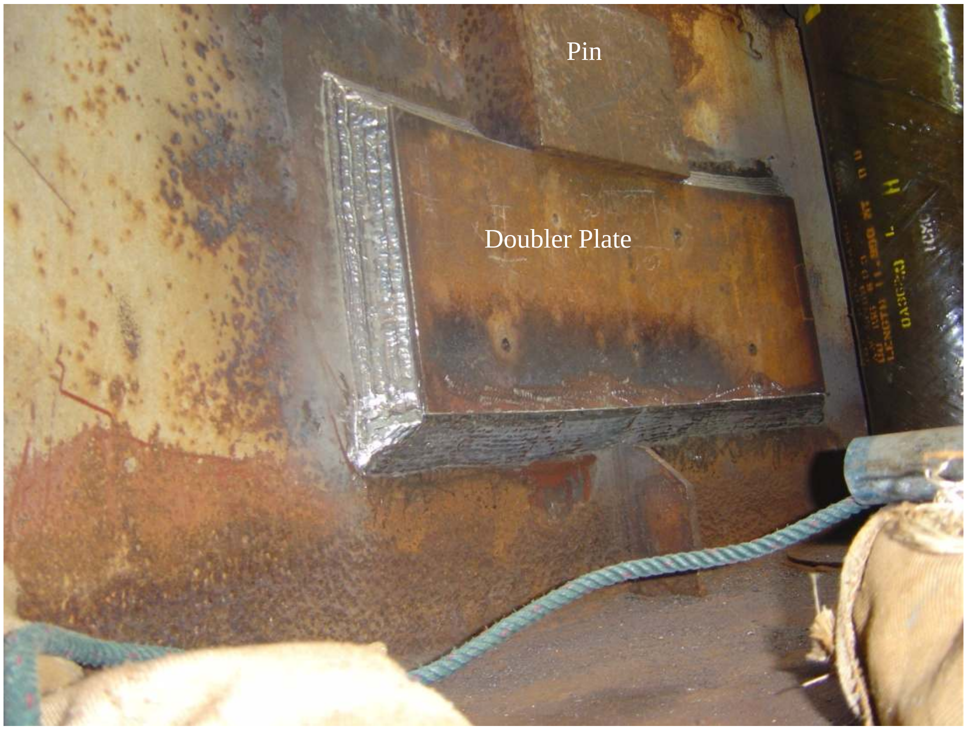

Figure 6: Additional Doubler Plates to Increase Bearing Capacity (12 Locations per Leg)

Design Challenges

Metocean conditions at the Maleo site were relatively benign and did not exceed the original design environment of the platform. Consequently, adequate structural performance could be readily demonstrated for storm and fatigue loads. The addition of new process equipment to the topsides increased wind loading which resulted in an increase in overturning moment on the structure. This did not significantly impact structural response. However, demonstration of overall stability of the soft clay foundation with the increased overturning moment was necessary. Seismic loading was not part of the original design basis of the platform and this presented a number challenges to the designers.

Storm Overturning Resistance

Due to the soft soil conditions at the site, the foundation failure mechanism that would lead to toppling, or least overturning resistance, was not certain. Certainly the ABS MODU Rules relating to mat rigs were deemed quite inappropriate. Deep-seated slip-circle failure was initially proposed. This resulted in relatively large overturning safety factors (OTSFs). An alternative method of strip footings to model the mat foundation was considered and developed. OTSFs predicted by this method were found to be extremely sensitive to the mat penetration achieved during installation, and to assumptions about how the penetration would disturb soil strengths in the mat-effected zone.

The design environmental load (wind, current and wave) in the 100-year storm developed a lateral load of 922 kips acting at 177 feet above the bottom of the mat with an associated overturning moment of 163,774 kip-feet.

Seismic Design

Safely placing a 30-year old converted jack-up rig on soft clay in a seismically active region offers further challenges. Foundation and structural integrity must be demonstrated for seismic loads. The class process using ABS rules required that the procedures of API RP 2A (API, 2000) be used to define the seismic analysis methodology and determine structural response for seismic loads.

A site specific seismic hazard was conducted to determine levels of ground shaking (Nisar, 2008). Ground motions at return periods of 200 years and 1000 years were selected as the strength level earthquake event (SLE) and ductility level event (DLE).

Response spectra calculations and pushover analyses were performed in the early stages of design. These indicated that the platform structural integrity was adequate. Base shear loads were high relative to the calculated foundation capacity for the SLE and DLE events and hence mat slippage was likely. However, it was only possible to estimate upper bounds for relative translational movements between the mat and soil and rotational movements could only be subjectively estimated. These results were severely limited as they were based on relatively crude geotechnical models where rate effects (especially those associated with soil and structural inertia in cyclic conditions) were difficult to evaluate.

Installation History and Class Approval Issues

Following conversion in Sharjah and Dubai, the platform was dry towed from the Arabian Gulf to its operating location offshore Indonesia.

The structure was installed in July 2006 and the mat penetration observed was more than expected. The penetration was not smooth with the mat remaining level at all times. During the installation and preloading (using only the hull compartments) the structure tilted, or rocked, over 2º bow downwards, and back by about 1º stern downwards, before ending up at about 0.3º stern down and 0.3º starboard down. While the rocking during installation may have resulted in deeper than expected penetrations, it was argued that the soil may have been weaker that predicted by the site investigation.

The method of strip foundation analysis to compute OTSFs showed large safety factors against overturning if the soil strengths from the original site investigation were used with the observed penetration depths. However, the deeper than expected penetration depths and soil strengths could not be rationalized. ABS did not accept that the minimum OTSF was greater than 1.5 in storm conditions. (Some background is given in Stewart, 2007.)

Furthermore, ABS did not accept that the upper bounds of relative translation between the mat and soil for both the SLE and DLE seismic events were acceptable for full classification approval.

Overcoming the Design and Analysis Challenges

GPS and STA saw the challenge, knew what was wanted, and assembled a team of respected geotechnical practitioners with considerable experience in offshore site investigation, characterization of soil conditions and assessment of foundation response. This team would address the challenges presented by the Maleo Field foundation. ABS also expanded their team with additional geotechnical and seismic hazard expertise as it was recognized that class approval required additional scrutiny above that in the published class rules. Both teams of geotechnical experts were incorporated into the overall project team as shown in (Figure 7).

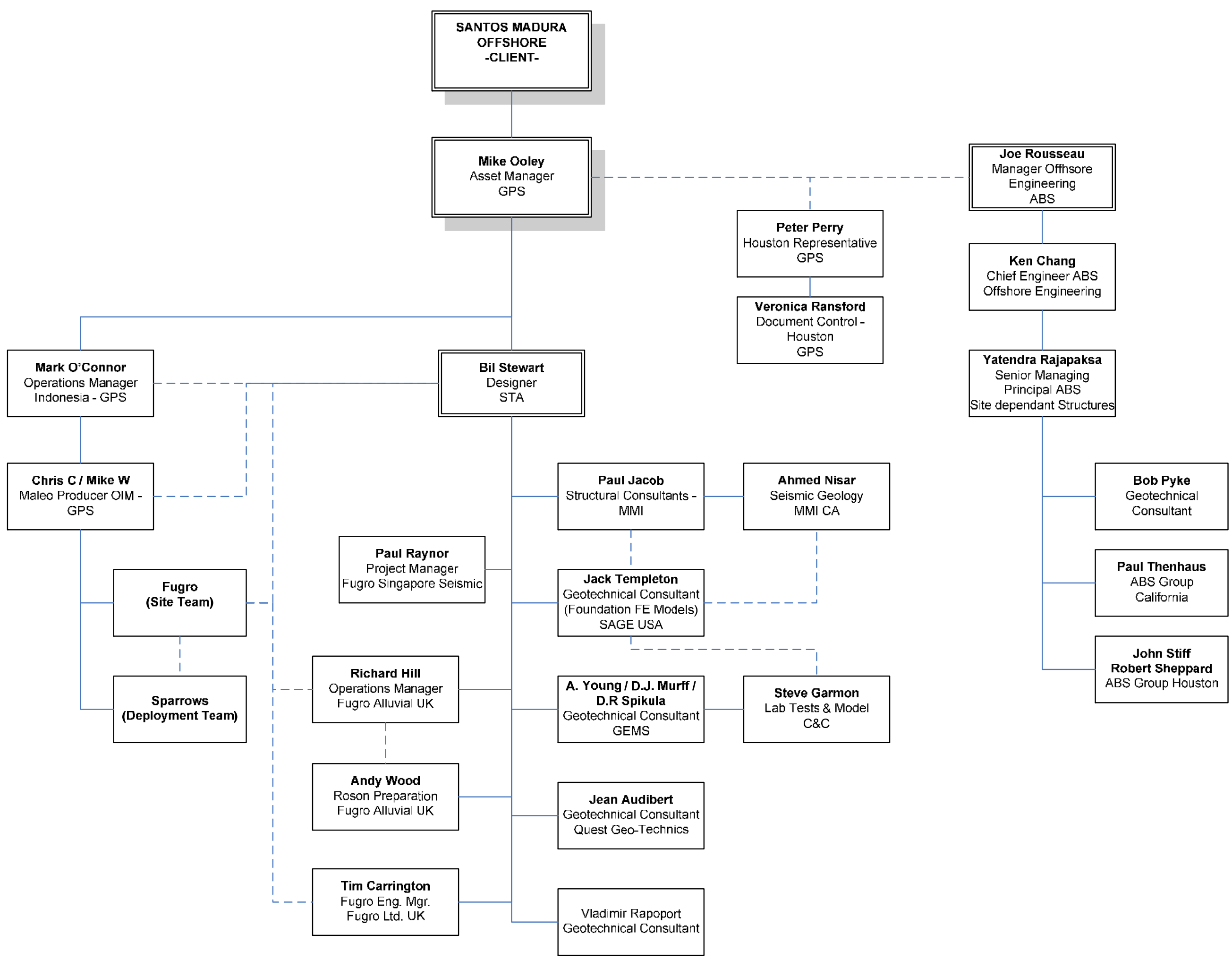

Figure 7: Overall Project Team for Maleo ABS Geotechnical and Seismic Approval Efforts

Opinion varied within the team on the failure mechanism that would dominate in overturning. It was proposed that a deep-seated slip circle type of mechanism may potentially control. Initial local failure around mat edges would lead to further embedment (penetration) of the mat as a whole, without toppling and increased bearing capacity resulting as a consequence of the clay's increasing strength with depth. Other opinions suggested local failure mechanisms would dominate.

Additional Site Investigation

The geotechnical team members were of the unanimous opinion that additional and more extensive geotechnical investigation of the site was required.

In December, 2006, a plan to proceed with two new geotechnical investigations was evolved. One would be a seismic investigation with two holes taken to 100 meters depth at a distance of about 100 meters away from the edge of the mat. The other would be a series of holes using pushed rods with the subsea equipment sat directly on the mat edge. Additionally, pushed rods would be used to deploy cones, t-bars and in-situ vanes away from the mat edge to investigate the extent of the mat effected zone. All in-situ measurements close to the mat would be made to a depth of 12 meters. Both investigations were undertaken by Fugro and completed in May 2007.

The advanced laboratory tests performed of the recovered samples from the seismic holes are the subject of a paper in this session (Spikula, 2008). Dynamic moduli and damping parameters were derived for use in time domain analysis work.

The analysis of the in-situ tests in the mat-effected zone are described in detail in this session (Audibert, et al., 2008). Detailed assessment of the soil strengths surrounding and beneath the mat after the mat had been in place for nearly one year is presented. Disturbance (local heave) of the seabed caused by the mat displacing soil as it penetrated is also described.

Addressing Overturning in Storm Conditions

An improved strip footing analysis method was evolved and is described in this session (Murff and Young, 2008). Using the new soils data it was concluded that a very conservative minimum OTSF of 1.64 was justified and thus one of ABS requirements for class (OTSF > 1.5) was satisfied.

Addressing Platform and Foundation Response Due to Seismic Loading

The concerns of the class society regarding mat slippage, overall stability on the foundation and pin loading could not be addressed by response spectra calculations. Consequently, further seismic assessment was conducted in the time domain. The problem was divided into two parts. Global stability was assessed by fully coupled soil structure interaction analyses (Templeton, 2008). This approach required an explicit representation of the soil mass below the mat, or the soil island as indicated in Figure 8.

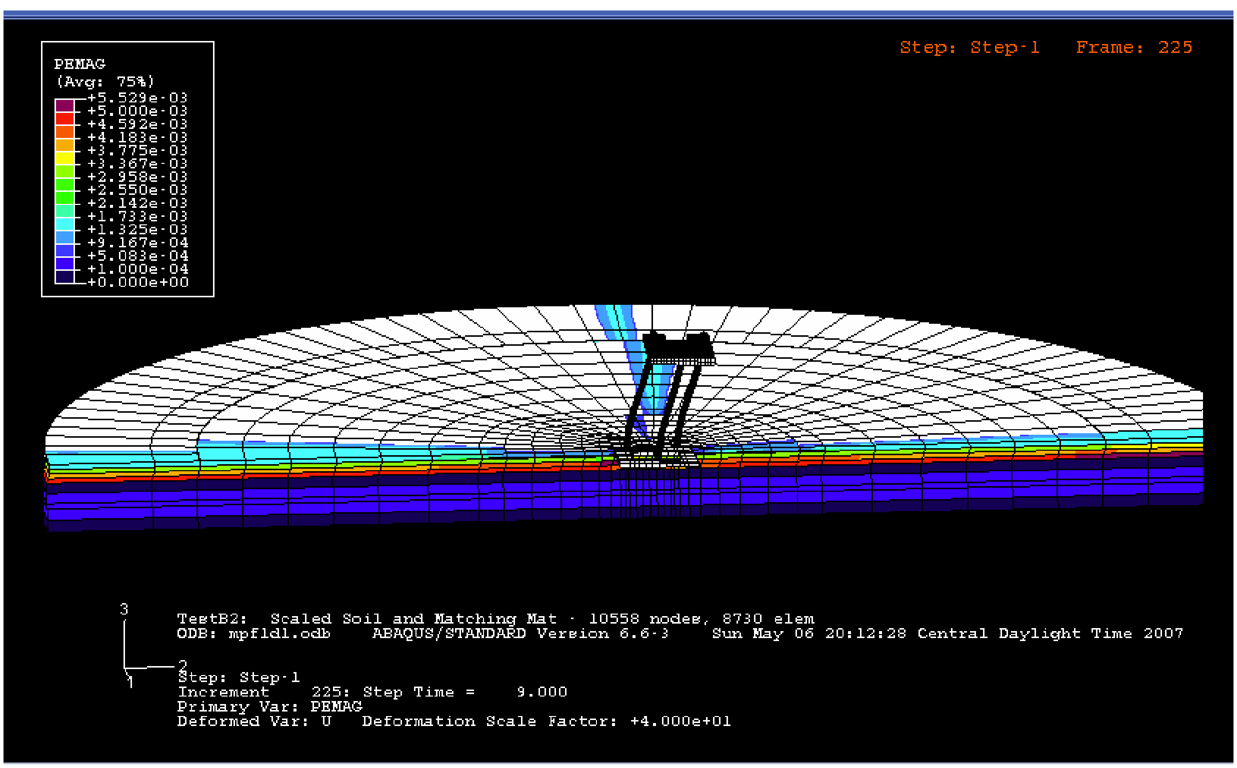

Figure 8 - Deformed Mesh Contour Plot of Plastic Strains for DLE 1 at 9.0 seconds

The model represented a soil region 150 ft deep by approximately ½ mile wide. The depth was selected to be sufficient to reach firm soil conditions and to be sufficiently below expected variations in upward wave propagation to make the results relatively insensitive to the precise location of this boundary.

A reduced version of the detailed ABAQUS structural model was placed on top of the soil model and fully linked through the mat. Run time efficiency was achieved by omitting the potential for uplift at each pin support pin. A complementary full structural model was developed to address pin gapping and results from the soil structural interaction analyses were used to drive the structural model (Stewart and Jacob, 2008). The approach was deemed to be appropriate only when it was determined (by numerous analyses) that local pin response did not impact overall global response of the platform. Extensive calibration was carried out between the models to ensure consistency of global response. All time history analyses were carried out with ABAQUS/Standard.

Three sets of acceleration time histories were developed as input for the soil structure interaction analyses and are described in this session (Nisar, 2008). These were based on were selected from historic earthquakes records that were considered representative for the site. To aid the selection, deaggregation of probabilistic seismic hazard analysis was conducted which identified that the most significant contribution to the site hazard is from earthquakes with magnitude around 7.0 at distances greater than 100 kilometers.

Time history analysis of the structure indicated that for the DLE event, the leg member loads did not develop utilization ratios (per API RP2A formulation) that exceeded unit. Pin loads were also found to be acceptable with peak bearing stresses approximately 60% of those used to size the additional doubler plates (original loads from pushover analyses). Intermittent uplift was observed at individual pin locations but at no time was all pins offloaded.

The maximum relative translational and rotational movements of the mat/soil were shown to be acceptable to the structure, the export gas pipeline and the well connections in both DLE and SLE events.

Summary and Conclusions

1. Application of MOPUs as marginal field development solutions will continue to be realistic options for E&P contractors.
2. In this case, more than usual engineering effort was focused on geotechnical and seismic data gathering, interpretation and dynamic analysis. To the author's knowledge, this was be the first complete, combined, finite element analysis of site response, soil-structure interaction and structural dynamic response to earthquake loading yet published, not only for a mobile offshore production unit but indeed for an offshore structure of any kind, thanks largely to Sage USA.
3. An improved understanding (and method of calculation) of static overturning resistance of mat-supported structures on soft clay soils was evolved.
4. Valuable data for the dynamic soil properties for one site in the Madura Straight was acquired and is presented.
5. The Maleo Producer is found to meet all structural requirements for full class approval in both storm and extreme seismic conditions with no foundation failure or excessive movement.

Acknowledgments

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