Challenges in Shallow Water Riser Design for FPSOs Installed in Campos Basin

R. Alvim - 2H
E. Ribeiro, E. Labanca – OGX
O. Veras - Insead

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Roberto Alvim
2H Offshore
Rio de Janeiro, RJ, Brazil

Elton J. B. Ribeiro
OGX Petróleo e Gás Ltda
Rio de Janeiro, RJ, Brazil

Edson L. Labanca
OGX Petróleo e Gás Ltda
Rio de Janeiro, RJ, Brazil

Otavio Veras
MBA Student at INSEAD formerly 2H Offshore Senior Engineer
Singapore

ABSTRACT

The selection of flexible riser configurations for production systems consisting of a turret moored Floating Production Storage and Offloading (FPSO) vessel for shallow waters can be as challenging as for deep waters. OGX is currently developing the Waimea and the Waikiki fields in shallow waters in the Campos Basin, offshore Brazil, using the turret moored FPSO’s OSX-2 and OSX-3, respectively. Both fields are identical in relation to the quantity of flexible lines: up to 26 lines, including umbilicals and flexible risers, with outer diameters ranging from 4inch to 9inch. This paper describes the steps followed to determine feasible riser configurations. The main challenges are discussed while different configurations are compared and evaluated.

KEY WORDS: Flexible Risers, Shallow Waters, FPSO, Campos Basin.

INTRODUCTION

OGX is a private Brazilian operator currently exploring hydrocarbons in shallow waters in the Campos basin, offshore Brazil. FPSO’s have been employed in all its field developments so far.

The most recent field developments are located in the Waimea and Waikiki fields, whose FPSO’s are named OSX-2 and OSX-3 respectively and are located in water depths of 105m and 135m. Both platforms are VLCC’s (Very Large Crude Carrier) and are kept in position by a single point mooring system (Turret). OSX-2 makes use of an internal turret, while OSX-3 adopts an external turret solution, Figure 1. At the time of writing, they are both under construction and are planned to be installed in 2013. Each FPSO will gather the oil and gas production from four subsea satellites wells and from nearby wells through dry completion Wellhead Platforms (WHP). Water injection systems to increase the oil production at a later stage are also planned to be installed from the WHP. Both OSX-2 and 3 are similar in many aspects including the flexible pipe properties adopted for the flowline and riser systems.

This paper describes the challenge of finding feasible riser configurations for the field developments of OSX-2 and OSX-3. The extensive study includes analysis of three different types of riser arrangements: free hanging catenary, pliant-wave and lazy-S. The intricacy of this work was complicated by the quantity of flexible lines each field is designed for: up to 26 lines, including umbilicals and flexible risers and flowlines with outer diameters ranging from 4inch to 9inch. Significant interference issues followed the whole process of the study. The relatively light weight of the flexible lines, geometrical limitations due to the shallow water depth and the highly dynamic vessel response added to the complexity of the task and made the riser system selected for the OSX-2 and OSX-3 vessels unique in the world.

Figure 1 – OSX-3 FPSO External Turret
PRELIMINARY FPSO SURVEY

A survey of the existing FPSOs in water depths below 200m was conducted at the early stage of the project in order to identify standard solutions previously considered for different fields. The riser configuration types and the quantity of flexible structures attached to each FPSO were investigated.

Figure 2 shows the quantity of flexible structures attached to the different FPSO’s and their respective water depths (Wilhoit and Supan, 2010). The points lying on the horizontal and/or vertical axes mean that either the information regarding the water depth and the number of risers is missing.

Figure 2 - Number of Risers installed at FPSO’s by Water Depth

A brief description providing the riser configuration types adopted for some key FPSO’s is also given in Figure 2. For example, the FPSO OSX-1 is designed with 10 risers in pliant-wave configuration and other 3 risers in lazy-S configuration through a single Mid-Water Arch (MWA).

With a total of 26 risers, the Challis Venture, in the Challis and Cassini fields, offshore Australia, decommissioned in January 2011, in a water depth of approximately 100m was identified with the maximum number of risers in shallow waters. However, this FPSO was connected to a 10.5m diameter SALM riser via a yoke. Other FPSO’s installed in shallow waters were identified with more than 15 risers, but using spread moored systems: the Etame, offshore Gabon, and the Okono/Okpono, offshore Nigeria.

The largest number of risers connected to a turret moored FPSO in shallow water was identified as the Alvheim FPSO, which has been designed to accommodate 14 risers and umbilicals. The lazy S configuration was chosen for all risers on this field using a total of 3 Mid-Water Arch’s.

The conclusion of this survey is that a shallow water field comprised of such a large number of risers attached to a turret moored FPSO has never been developed, demonstrating that the riser system designs for the OSX-2 and OSX-3 are firsts of their kind.

SYSTEM DESCRIPTION

The FPSO OSX-2 is an internal turret moored system and will be located at the extreme South of the Campos Basin in 135m water depth and the FPSO OSX-3 is an external turret moored system and will be located in the Southern region of Campos Basin in 105m water depth.

Both systems will gather the oil production from satellites wells and a WHP through dry completion wells. The satellite well bundles will be comprised of: 6” flexible production lines, 4”/6” flexible gas lift/service lines and electrical/hydraulic control umbilicals.

The produced oil from the WHP will be exported to the FPSO by an 8” flexible production line and will import electrical power (three x 5” power cables), gas for injection and lift method (two 6” flexible lines), diesel for service (one 4” flexible lines) and water for reservoir injection (one 8” flexible line).

Figure 3 shows the OSX-2 turret arrangement and the Figure 4 shows the OSX-3 turret arrangement. It can be observed that a large number of risers are planned for both fields. It should be noted that the slots #4 and #20 of the OSX-2 FPSO and the slots #8, #15 and #19 of the OSX-3 FPSO are spare. The properties of the flexible risers and umbilicals used in the riser analyses of OSX-2/3 are presented on Table 1.
Table 1 – Riser and Umbilical Structural Properties

<table>
<thead>
<tr>
<th>Function</th>
<th>Outer Diameter (mm)</th>
<th>Inner Diameter (mm)</th>
<th>Effective Inner Diameter (mm)</th>
<th>Weight Empty in Air (kgf/m)</th>
<th>Weight Empty in Sea Water (kgf/m)</th>
<th>Weight Full of Hydraulic Fluid (kgf/m)</th>
<th>Weight Full of Seawater Fluid (kgf/m)</th>
<th>Bending Stiffness in Air (kN.m/m)</th>
<th>Axial Stiffness in Air (kN/m)</th>
<th>Axial Stiffness in Sea Water (kN/m)</th>
<th>Operating Bending Radius (m)</th>
<th>Failure Tension (kN)</th>
</tr>
</thead>
<tbody>
<tr>
<td>4&quot; Service/GL</td>
<td>164</td>
<td>102</td>
<td>106.1</td>
<td>44.3</td>
<td>53.4</td>
<td>31.6</td>
<td>3.64</td>
<td>240</td>
<td>1E+05</td>
<td>1.85</td>
<td>3.91</td>
<td>7452</td>
</tr>
<tr>
<td>5&quot; PU</td>
<td>126</td>
<td>#</td>
<td>#</td>
<td>35.2</td>
<td>22.3</td>
<td>67.10</td>
<td>13.19</td>
<td>2.3</td>
<td>1.987</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6&quot; TBU</td>
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<td>#</td>
<td>#</td>
<td>34.8</td>
<td>0.2</td>
<td>23.8</td>
<td>3.8</td>
<td>223</td>
<td>4E+05</td>
<td>2.3</td>
<td>1.987</td>
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<tr>
<td>6&quot; EPHU</td>
<td>153</td>
<td>#</td>
<td>#</td>
<td>34.8</td>
<td>0.2</td>
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<td>3.8</td>
<td>223</td>
<td>4E+05</td>
<td>2.3</td>
<td>1.987</td>
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<tr>
<td>6&quot; GL/Gas Injection</td>
<td>250</td>
<td>152</td>
<td>159</td>
<td>111</td>
<td>131</td>
<td>80.4</td>
<td>25.7</td>
<td>1787</td>
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<td>2.63</td>
<td>1938</td>
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<tr>
<td>6&quot; Production/Testing</td>
<td>247</td>
<td>152</td>
<td>157</td>
<td>114</td>
<td>134</td>
<td>84.9</td>
<td>33.6</td>
<td>2745</td>
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<td></td>
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<tr>
<td>8&quot; Production</td>
<td>316</td>
<td>203</td>
<td>209</td>
<td>182</td>
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<td>137</td>
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<td>8&quot; Water Injection</td>
<td>205</td>
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<td>203</td>
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<td>58.1</td>
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<td>2E+05</td>
<td>2.77</td>
<td>2973</td>
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<tr>
<td>9.13&quot; Gas Export</td>
<td>348</td>
<td>232</td>
<td>238</td>
<td>209</td>
<td>255</td>
<td>157</td>
<td>124</td>
<td>8203</td>
<td>3E+05</td>
<td>3.91</td>
<td>7452</td>
<td></td>
</tr>
</tbody>
</table>

* for umbilical the hoses are full of hydraulic fluid and interstices.

FEASIBILITY ASSESSMENT METHODOLOGY

The feasibility assessment was conducted in accordance with the sequence shown in Figure 5. A different configuration is investigated if the design criteria are not satisfied in any of the steps described below.

Figure 5 – Feasibility Analysis Sequence

Preliminary Configuration Assessment

Static analysis is conducted in order to identify feasible configurations for all flexible risers and umbilicals attached to each FPSO. Due to geometrical restraints to assemble the I-Tubes at the OSX-2 turret and the riser order previously defined for both OSX-2 and OSX-3 turrets, the same top angle was adopted for all flexible structures attached to the same FPSO. The top angle of 7 degrees was adopted for the OSX-2 risers and 9 degrees for the OSX-3 risers. The configuration is considered valid for further analysis if the minimum resultant bending radius (MBR) along the structure is above the operating bending radius specific for each structure type. Preliminary interference issues are also assessed in this phase, such as sag-bend interference with the mudline and hog-bend interference with the FPSO for the compliant configurations.

Extreme Storm Analysis

The configurations selected in the preliminary assessment are evaluated considering a load case matrix developed in accordance with the environmental data available for the field and vessel headings expected for the turret moored FPSO’s. Regular wave approach is adopted for the analysis.

A total of 8 loading directions are considered, with respect to the riser plane: Near, Cross Near 1, Transverse 1, Cross Far 1, Far, Cross Far 2, Transverse 2 and Cross Near 2. Each loading direction corresponds to a vessel offset direction. Directional mean vessel offsets are considered for the analysis in accordance with the information provided by the designer of the mooring system.

100year return current loading together with 10year return wave loading (and vice-versa), applied at the offset direction, or 22.5deg off offset direction are considered as summarized in Table 2, for a given Offset direction. A total of 64 loading conditions is analyzed by multiplying the 8 loading conditions summarized in Table 2 by the 8 loading directions.

Table 2 – Extreme Storm Load Case Summary for Each Loading Direction

<table>
<thead>
<tr>
<th>Load Case #</th>
<th>Current Direction</th>
<th>Current Return Period (yrs)</th>
<th>Wave Direction</th>
<th>Wave Return Period (yrs)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Aligned with offset dir.</td>
<td>10</td>
<td>Aligned with offset dir.</td>
<td>100</td>
</tr>
<tr>
<td>2</td>
<td>Aligned with offset dir.</td>
<td>100</td>
<td>Aligned with offset dir.</td>
<td>100</td>
</tr>
<tr>
<td>3</td>
<td>+22.5deg off offset dir.</td>
<td>10</td>
<td>-22.5deg off offset dir.</td>
<td>100</td>
</tr>
<tr>
<td>4</td>
<td>+22.5deg off offset dir.</td>
<td>100</td>
<td>-22.5deg off offset dir.</td>
<td>100</td>
</tr>
<tr>
<td>5</td>
<td>-22.5deg off offset dir.</td>
<td>10</td>
<td>+22.5deg off offset dir.</td>
<td>100</td>
</tr>
<tr>
<td>6</td>
<td>-22.5deg off offset dir.</td>
<td>100</td>
<td>+22.5deg off offset dir.</td>
<td>100</td>
</tr>
<tr>
<td>7</td>
<td>Aligned with offset dir.</td>
<td>100</td>
<td>+90deg off offset dir.</td>
<td>1</td>
</tr>
<tr>
<td>8</td>
<td>Aligned with offset dir.</td>
<td>100</td>
<td>-90deg off offset dir.</td>
<td>1</td>
</tr>
</tbody>
</table>

The minimum and maximum content densities expected for the life of both fields are considered in the analysis as well as the minimum and maximum FPSO drafts. Marine growth is taken into account in this assessment.

Abnormal conditions are also evaluated, considering a 25deg vessel list together with 1yr return current and wave loadings.

Marine growth is considered for the analysis in all loading conditions. In addition to the design criteria established for the preliminary configuration assessment, compression in the flexible structures is evaluated and compared against their limits. When applicable, minimum tether tension is also assessed.

Interference Analysis

Due to the nature of the field layout, with a large number of structures attached to each FPSO, interference is the key challenge to designing the riser system. In some cases, 9 risers are present in a single turret sector. A load case matrix similar to the one considered for extreme storm analysis is considered for interference.

A finite element model with all risers, umbilicals and mooring lines is constructed and preliminary quasi-static analysis considering 100yr return current loading and directional extreme offsets is conducted in order to identify if contact is likely to occur between any of the subsea structures. Depending on analysis results, further investigations are conducted on the configurations, including wave loadings.

During this analysis phase, the minimum clearance between the risers and the mooring lines or any other subsea structure is assessed. Each structure pair must present in all loading conditions a minimum clearance larger than the sum of their outer diameters, as recommended by DNV-RP-F203. Interference between the risers and the umbilicals is left to be checked during the detailed design phase, but are assumed to be acceptable provided that the contact energy obtained from the dynamic simulations is shown to be within safe levels.

FREE HANGING CATENARY CONFIGURATION ASSESSMENT

Typically, a free hanging catenary configuration is not recommended for risers and umbilicals operating in shallow waters. This is because the dynamic motions induced at the top of the risers by wave loading are not sufficiently damped along the structure to avoid high curvatures at the touchdown zone. This violating the operating bending radius of the structure and produces high levels of compression at the TDP.
Furthermore, the vessel offsets in terms of percentage of water depth are significantly higher than the offsets usually considered in deepwater applications, increasing the top angle range around its nominal value.

Nevertheless, a preliminary assessment is conducted for the 6inch production and 6inch gas lift risers in order to assess the response of the risers and confirm or not that this is unacceptable. This assessment is conducted only for the OSX-2 development as it shows less severe dynamic response than the OSX-3, mainly due to differences related to the turret location with respect to the vessel center of motion.

Both structures analyzed presented minimum bending radii below the operating bending radius at the touchdown region under 100yr return wave loading coming from the Southwest, which is the most critical wave loading present in the Campos Basin, confirming the unfeasibility of this type of configuration for such applications.

**PLIANT-WAVE CONFIGURATION ASSESSMENT**

As the preliminary studies confirmed that the free hanging catenary configuration does not work in such water depths, it was necessary to consider compliant configurations for the OSX-2 and OSX-3 risers. The lazy-wave configuration was disregarded due to the large number of risers attached to the FPSO and the proximity between the TDP’s and buoyancy modules expected for both fields which would lead to severe interference issues.

The pliant-wave configuration was selected because the suspended riser region close to TDP is tethered, restraining considerably the lateral motions in this region.

The first challenge of this is study is to find feasible configurations for diverse flexible structure types considering similar top angles. A preliminary study is conducted, varying several parameters such as net buoyancy, length of the buoyant section, suspended length of the riser and tether positioning. The same configuration is analyzed under 100yr return period currents applied to the near and far offset directions with respect to the riser plane. The minimum and maximum fluid densities are also applied in order to verify if the resulting catenary profiles are acceptable in terms of interference with the vessel and the seabed.

Once the preliminary configurations are selected, extreme storm analysis is conducted in order to verify if the proposed configurations are valid under combined extreme wave, current and offset loading. If not, a different configuration is selected following an iterative approach. When all configurations are considered valid, interference between the adjacent structure pairs is conducted. Due to proximity of the subsea structures, as shown in Figure 6, it is considered that contact between two lines is allowable if the contact occurs at the sections without buoyancy of both structures. The interference analysis classifications are summarized in Table 3, and the results summarized in Figure 7, considering the color scheme established in Table 3. The analysis results show that almost 60% of the structure pairs are found to present un-permissible clashing for the OSX-3 configurations. The same trend was found for the pliant-wave configurations selected for the OSX-2 development. The current loadings are found to be the main issue to obtain feasible pliant-wave configurations from interference standpoint.

In summary, interference is a complex problem to be solved due to the large number of flexible structures planned for both fields. Interference between the buoyant sections of the pliant-wave risers with adjacent structures and interference between the risers and the mooring lines were identified for several structures under normal operating and extreme loading conditions. For this reason, the pliant-wave configuration is not recommended to be adopted for the OSX-2 and the OSX-3 risers.

![Figure 6 – OSX-2 Interference Analysis Model](image)

![Figure 7 – OSX-3 Interference Analysis Qualitative Results Summary](image)

**LAZY-S CONFIGURATION ASSESSMENT**

The lazy-S configuration is identified as an alternative to mitigate the severe interference issues. In the lazy-S configuration there is a subsea buoy, also known as Mid Water Arch (MWA), which consists of a subsea buoyancy tank assembly, two tethers and a gravity base. The buoyancy tank assembly provides net buoyancy that withstands the forces imposed to the structure by the risers, as shown in Figure 8. The main advantage of using the Lazy-S configuration in comparison with the pliant wave configuration is that a number of risers can be grouped and attached to a single MWA, giving more room between the mooring
lines and adjacent risers. Another advantage is that the TDP response is significantly improved with the addition of the buoy, while absorbs the tension variation induced by the FPSO motions.

Each of the three sectors delimited by the mooring lines are planned to have 3 Mid-Water Arches (MWAs), giving a total of 9 MWAs for both the OSX-2 and OSX-3 fields. The proposed arrangements consist of a number of flexible structures, varying from 2 to 4, connected to a single MWA. The reason for adopting the use of 3 MWAs on each sector is to minimize the buoyancy requirements and subsequent increased tank sizes, affecting the selection of installation resources.

The Mid-Water Arches are assumed with a net upthrust of approximately 76 Tonnes.

Preliminary static analysis is conducted in order to select the lazy-S configurations for both fields, following the same approach considered for the pliant-wave configurations. In order to achieve the required top angle of 9 degrees and improve the interference and extreme storm response, some light structures attached to the OSX-3 FPSO, such as umbilicals and service lines, require ballast modules.

The lazy-S flexible structure distribution per each MWA and the configuration summary after the iterative analysis cycles considering extreme storm and interference analysis are given in Table 4 for OSX-2 and Table 5 for OSX-3, in accordance with the schematic shown in Figure 9.

The configurations selected are analyzed dynamically in order to evaluate the riser system response under extreme and accidental conditions.

The effective tension envelopes at the hang-off are shown in Figure 10 for the FPSO OSX-2 and Figure 11 for the FPSO OSX-3. Although the riser structural properties and the internal fluids considered for both developments are the same, the maximum effective tension and the overall ranges found for the FPSO OSX-3 are significantly higher than the FPSO OSX-2. Furthermore, the environmental conditions considered for the analysis are the same.

The main reason for this is because the FPSO OSX-2 is designed with an internal turret located approximately 110m from the vessel CoG. The FPSO OSX-3 is designed with an external turret, located approximately 190m from the CoG, i.e. 72% further from the FPSO centre of gravity than OSX-2.
Hence, although the RAOs for the both platforms are similar, the dynamic amplification of the pitch is considerably higher for the FPSO OSX-3, as illustrated in Figure 12.

Figure 10 – Effective Tension Ranges at the Hang-Off – OSX-2

Figure 11 – Effective Tension at the Hang-Off – OSX-3

Figure 12 – Timetrace Comparison of Hang-off Vertical Motions

The considerably higher dynamic effects at the top of the risers and umbilicals for the OSX-3 are found to affect significantly the overall response of the system, as seen for example, on tether tension envelopes for OSX-2, Figure 13 and OSX-3 Figure 14. Note that almost all OSX-3 tethers present minimum effective tensions below 100kN.

Both examples show that finding valid configurations for the OSX-3 development is an even harder task than finding the OSX-2 riser configurations.

The minimum bending radius along the risers and the umbilicals are verified in order to confirm the fitness-for purpose of the flexible structures proposed for both fields.

Figure 13 – Effective Tension at the MWA Tethers – OSX-2

Figure 14 – Effective Tension at the MWA Tethers – OSX-3

After confirming that the flexible structures attached to all MWAs and their selected configurations are valid under extreme storm conditions, interference analysis is conducted to verify if they are fit to work together. Orcaflex models are built considering all subsea structures proposed for both fields.

The minimum clearance between the flexible structures and the other structures (such as mooring lines, MWAs and tethers) within the same sector is assessed. As a means to optimize the Lazy-S riser configurations of the FPSO OSX-3 for interference issues, most of the umbilicals and 4inch Service flexible risers and the 8inch Water Injection of MWA-9, consider ballast modules installed along the line in the region between the bellmouth and the MWA, as previously mentioned. Different distances from MWA to the vessel turret for
adjacent MWAs and different heights for each MWA are some additional measures considered to mitigate the interference issues.

Figure 15 – OSX-2 Interference Analysis Model

One of the critical interference issues is to avoid clashing of any flexible structure and umbilicals against the mooring lines. The lightest structures such as umbilicals and the 4” Service risers present large lateral displacements under extreme transverse current loading. Additionally, the effect of wave loading at the top section of the riser is found to reduce significantly the minimum clearances with the mooring lines.

The sagbend displacements are also found to be an issue, due to the proximity between the 3 MWAs of each sector. Interference between the light structures and the MWAs and/or tethers are found to be critical.

The interference analysis results are summarized in Table 6 for OSX-2 and Table 7 for OSX-3. Both results are for the Northeast Sector of each field. This assessment only considers the evaluation of impermissible clashing between the flexible structures and the mooring lines or any other subsea structure. The analysis results show that the interference response for the FPSO OSX-3 field is also more critical than the FPSO OSX-2, mainly due to the more severe dynamic behavior imposed by the OSX-3 vessel motions.

As identified for the pliant-wave configurations, the current loadings are found to be the main issue for interference. However, wave loading is found to affect significantly the interference response, especially for the OSX-3, where the risers are connected to an external turret.

<table>
<thead>
<tr>
<th>Table 6 – Interference Analysis Summary for Sector NE – OSX-2</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sector NE Cases 1 and 2 – Dynamic</strong></td>
</tr>
<tr>
<td><strong>MWA-1</strong></td>
</tr>
<tr>
<td>4” Service</td>
</tr>
<tr>
<td>5” Umbilical</td>
</tr>
<tr>
<td>6” Production</td>
</tr>
<tr>
<td>Spars</td>
</tr>
<tr>
<td>4” Service</td>
</tr>
<tr>
<td>4” Power Umbilical</td>
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<tr>
<td>4” Power Umbilical</td>
</tr>
<tr>
<td>4” Production</td>
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</tbody>
</table>

*Minimum clearance values given in meters

<table>
<thead>
<tr>
<th>Table 7 – Interference Analysis Summary for Sector NE – OSX-3</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Sector NE Case 1</strong></td>
</tr>
<tr>
<td>4” Service</td>
</tr>
<tr>
<td>5” Umbilical</td>
</tr>
<tr>
<td>6” Production</td>
</tr>
<tr>
<td>Spars</td>
</tr>
<tr>
<td>4” Service</td>
</tr>
<tr>
<td>5” Umbilical</td>
</tr>
<tr>
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<tr>
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<tr>
<td>6” Production</td>
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<tr>
<td>Spars</td>
</tr>
<tr>
<td>6” Production</td>
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</tbody>
</table>

*Minimum clearance values given in meters

**CONCLUSIONS**

From the studies conducted the key conclusions are:

- Never before has such large number of risers proposed for the OSX-2 and OSX-3 developments have been used in shallow waters using a turret moored FPSO;
- Free hanging catenary riser configurations are not feasible for such water depths as the curvatures at the TDP are severe due to large FPSO offsets and wave induced motions;
- Pliant-wave configurations are feasible in terms of extreme storm response, however interference could not be solved for the proposed layouts of both the OSX-2 and OSX3 FPSOs;
- Lazy-S configuration concept is feasible for both fields;
- The development of the OSX-3 riser configurations is significantly more complicated than OSX-2 mainly because of the external turret concept which is found to increase significantly the dynamic response of the riser systems;

The results obtained from the conceptual studies and summarized in this paper indicate that the lazy-S concept is technically feasible from the stand point of operation of the flexible pipe, but there are still interference issues to be verified, such as the interference between the flexible lines and umbilicals.

For this reason, it is recommended that further analysis shall be conducted in order to evaluate the contact energy levels and verify its acceptability. Other essential structural verification to be assessed is the evaluation of the fatigue response of the flexible structures.

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Further improvements for the OSX-3 FPSO riser system may also be adopted, such as an increase of the MWA net buoyancy in order to increase its stability and reduce the dynamics along the riser sag bend and TDP.

ACKNOWLEDGEMENTS

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