ABSTRACT

The proposed paper shall list and present the issues from a mooring and hydrodynamic point of view relative to the design of a floating structure connected to another floating structure in surface and to the seabed with traditional anchoring legs, such as a Flotel with an FPSO. The paper will propose tentative ways to properly design the connections between the two floating structures which will limit their relative excursions in order to allow the setting of a gangway between them. In addition, the design should forbid at any time any potential contact between the two structures in intact and damage conditions, and should trigger at any time acceptable tensions in the various anchoring and mooring systems. The paper will address the appropriate mooring and hydrodynamic analysis to be used for such exercise. Safety issues such as quick disconnection in case of fire are investigated. Operational issues are to be discussed as well.

INTRODUCTION

The concept of Flotel or in another term the possibility of adding temporary a floating structure to another floating structure is rather popular nowadays, the aim being to add bed capacity, working area and others during temporary development work. Usually the two floating structures are connected by the means of a gangway, allowing the continuous transfer of personnel between the two structures. It should remain accessible for most of the time, except for the extreme weather conditions to be defined.

The purpose of the present paper is to review the different design parameters proper to the use of a gangway and then assess the feasibility of a purposely built gangway between a Flotel barge when connected to a permanently spread-moored FPSO in relatively mild weather conditions, such as in West Africa, based on numerical mooring and hydrodynamic analysis using state-of-the-art mooring and hydrodynamic tools.

In our example, the extreme loading conditions (ballast and fully loaded) of the FPSO and the operational loading condition of the barge have been considered.

Several weather conditions were analysed:

- 1Y weather condition
- 10Y weather condition

The gangway is supposed to be connected during 1Y and 10Y weather conditions, even so if for that latter the transit of people will not be allowed. In addition the connections between the Flotel and the FPSO shall be released in case of emergency in order to move the Flotel away from the FPSO to a safe distance.

Furthermore, the response of the two units has been considered when in intact condition but also when one line of the Flotel anchoring system is broken or when one line of the FPSO mooring system is broken.

No dynamic winching was implemented in our calculations.

The software used for the hydrodynamic analysis is HYDROSTAR, developed and maintained by Bureau Veritas.

The software used for the mooring analysis is ARIANE-3Dynamic, developed and maintained by Bureau Veritas.
ARIANE-3Dynamic was validated by NMD and is recognised by SHELL and ELF standards for mooring analysis.
All the calculations were performed against Bureau Veritas Recommended Practice for Mooring Analysis [1].

In addition, some industry standards have been selected regarding the safe distance to be kept at any time between the two structures: 10m, which is confirmed as well by typical Drilling Standards. It should be noted that an excursion reserve of 1.5m of the specified maximum excursion of the gangway is to be included, during normal operation.

NOMENCLATURE OF THE PAPER
The proposed layout of the paper is as follow:
- SETTING OF THE SYSTEM
- SPECIFIC REQUIREMENT
- HYDRODYNAMIC ANALYSIS
- MOORING ANALYSIS
- RECOMMENDATIONS

SETTING OF THE SYSTEM
The proposed gangway shall connect a Flotel to a permanently moored FPSO in a spread configuration. For operational issues, the Flotel will be connected at the stern of the FPSO by means of hawser and to the seabed by six anchoring lines.

The initial distance between the two vessels for the Barge case is set at 40.0m, when the FPSO is in ballast loading condition.

Two loading conditions of the FPSO and one loading condition of the Flotel barge have been analysed:
1. FPSO ballast - Flotel barge fully loaded,
2. FPSO fully loaded - Flotel barge fully loaded,

It is supposed that the FPSO draft variations will not change significantly the dynamic horizontal distance between the two vessels.

For each loading condition, hydrodynamic calculation models were built based on the following data.

FPSO
A mesh has been created for each loading condition integrating the below data:

<table>
<thead>
<tr>
<th>Loading condition</th>
<th>Full</th>
<th>Ballast</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water depth (m)</td>
<td>1350.00</td>
<td></td>
</tr>
<tr>
<td>LBP (m)</td>
<td>300.00</td>
<td></td>
</tr>
<tr>
<td>Breadth (m)</td>
<td>59.60</td>
<td></td>
</tr>
<tr>
<td>Draft (m)</td>
<td>22.7</td>
<td>10.50</td>
</tr>
</tbody>
</table>

The damping coefficients used in the mooring analysis follow the proposed formula to be found in the BV Mooring RP [1].

For the hydrodynamic analysis quadratic viscous roll damping has been implemented.

Flotel - Barge
A mesh has been created for the unique loading condition integrating the below data:

<table>
<thead>
<tr>
<th>Loading condition</th>
<th>Fully Loaded</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water depth (m)</td>
<td>1350.00</td>
</tr>
<tr>
<td>LOA (m)</td>
<td>100.00</td>
</tr>
<tr>
<td>Breadth (m)</td>
<td>30.00</td>
</tr>
<tr>
<td>Depth (m)</td>
<td>7.00</td>
</tr>
<tr>
<td>Draft (m)</td>
<td>4.00</td>
</tr>
</tbody>
</table>

The damping coefficients used in the mooring analysis follow the proposed formula to be found in the BV Mooring RP [1].

For the hydrodynamic analysis some quadratic viscous roll damping has been implemented.

As the two floating structures are moving relatively to each other, the length of the gangway shall be variable, therefore a telescopic gangway is necessary.

For the attachment of the gangway, two configurations have been analysed; one mainly transversal and the other mainly longitudinal. See Figure 1.

For alternative 1, Flotel Barge, in static without external load, DX=39.1m, DY=5.1m and D=39.43m

For alternative 2, Flotel Barge, in static without external load, DX=36.1m, DY=36.0m and D=50.98m

SPECIFIC REQUIREMENT
The description of the telescopic gangway proposed for that project is as follow:
- One connection point fixed on the Flotel for the 6 degrees of freedom,
- One connection point on the FPSO which should be freed for the rotations and for the radial translation and fixed for the others,
- A main fixed part whose length is mainly defined by the initial and the minimum distance between the two extremities on each vessel,
- A telescopic part whose length should cope with the extreme motions of the connections points. This extended part should be able to slide into the main fixed part.

As the two vessels are going to experience in-plane and out-of-plane motions under the effect of wind, wave, current and the response of the various anchoring legs, it is possible to address such motions by using Mooring and Hydrodynamic software. Therefore the necessary information to be provided in order to
properly design the gangway should include (but not be limited to, as we do not address the structural strengths of the gangway):

**Maximum and minimum span of the gangway**
Such information is necessary to set the length of the fixed and telescopic parts of the gangway. A first minimum span estimation of the gangway is necessary in order to assess the clearance zone around the contact point on the FPSO to avoid any potential clashing between the main part of the gangway rotating around its FPSO connection with existing structures on deck. As any traditional moored units, the response of each unit will be governed by a wave frequency response around a low frequency response. Therefore to ease the span estimation and to keep a certain level of conservatism, each response may be analysed separately and added to each other.

**Low frequency response**
The span estimation in low frequency should take into account the response of the two systems by considering the effect of wind, current and slow drift on the two floaters and the restoring forces of each anchoring and mooring systems. Typically such assessment is the scope of mooring analysis with the ability to deal with two floaters connected to each other. In our case, the mooring analysis software ARIANE was modified in order to cope with multi-connections, multi-vessels systems. When possible the screen effects for the wind, current and slow drift loads should be considered as they may impact onto the responses of the two units.

The scope of the necessary mooring analyses should encompass the following scenarios:
- in intact condition for both floaters
- in intact condition for the Flotel and in damage condition for the FPSO. The selection of the line(s) to be broken and the environmental conditions should cover the cases where the FPSO will move respectively towards and away from the Flotel.
- in damage condition for the Flotel anchoring to the seabed and in intact condition for the FPSO. In that case only an estimate of the minimum gangway deflection is relevant. The selection of the line(s) to be broken and the environmental conditions should cover the cases where the Flotel will move respectively towards the FPSO.

**Wave frequency response**
The motions of the floaters at wave frequency should be considered in order to estimate the gangway characteristics. Both in-plane and out-of-plane relative motions have to be assessed. Such assessment could be performed in the frequency domain by typical multi-bodies hydrodynamic analysis. The out-of-plane relative motions will determine the clearance around and the necessary mechanical deflection of the connecting points. Therefore the loading conditions of the two floaters have an impact and the associated trim as well and should be investigated.

**Maximum accelerations**
In order to properly operate the gangway, it is necessary to evaluate and control the acceleration of the gangways at the extremities of that latter and at any points when relevant. Such analysis could be performed in the frequency domain by traditional multi-bodies hydrodynamic tools. Such analysis should allow as well determining the limiting weather conditions under which the gangway should remain connected or not.

**Minimum distance between the two structures**
In order to ensure that when connecting or disconnecting the gangway, that latter will not be smashed against one of the vessel decks, it is necessary to control the relative velocity of the gangway with respect to the FPSO deck vertical motions. Such analysis could be performed in the frequency domain by traditional multi-bodies hydrodynamic tools.

**Relative rotation angles**
In order to properly design the mechanical characteristics of the gangway connection points, it is necessary to ensure that the maximum relative roll motions between the two floaters are within the mechanical limits. In addition, the maximum relative yaw and pitch angles should be assessed in order to ensure that the clearance around and the necessary mechanical deflection of the connecting points are respected. Therefore the loading conditions of the two floaters have an impact and the associated trim as well and should be investigated.

**Hydrodynamic acceleration and motion Fatigue**
For the proper design of the gangway, it should be necessary to estimate the various levels of accelerations & motions at the top and base of the gangway and their number of occurrence for
the various weather conditions to be met during the life of the project, in order to estimate wearing and any other structural defects factors.

HYDRODYNAMIC ANALYSIS

The present chapter summarises the main assumptions and results of the hydrodynamic analysis of the Flotel with the FPSO. The main concern of this study is to assess the relative motions of the two bodies.

This study has provided the first input for making a specification for the construction of the gangway and to give the RAO for a mooring calculation of the bodies. Specific diffraction-radiation calculations have been performed using appropriate 3D mesh of the models.

The calculations were carried out by means of the BUREAU VERITAS computer program HydroSTAR. HydroSTAR is a 3D diffraction-radiation program based on potential theory for both first and second orders. Numerical developments use the singularity method (Kelvin's sources) for the first order solution and Molin's method for the second order solution.

For such system configuration, the screen effect or the hydrodynamic interaction between the two bodies is not negligible and may have some beneficial effects such as the dampening of the Flotel motions for some wave directions. Therefore such interaction is to be implemented in the hydrodynamic analysis.

The hydrodynamic calculations have to be performed for at least 9 wave headings: 180, 202.5, 225, 247.5, 270, 292.5, 315, 337.5 and 360 degrees, assuming that the system is symmetrical along its longitudinal axis (Heading 180: head sea).

It is necessary to take into account the influence of the stiffness on the motions of the two bodies.

In addition it is necessary to perform sensitivity analysis by varying the wave period, the wave peakness parameter in order to ensure proper representations of the various phenomena.

Obviously the position of the gangway on the two floaters will have an impact on the results; as presented, two configurations were analysed for the gangway position. Furthermore, in order to reduce the relative motions, some additional runs were performed by inputting the contact point on the Flotel closer to the mid-ship.

Multi-body hydrodynamic calculation

The hydrodynamic calculation which takes into account the shadow effect is based on the following theoretical background:

Multi-body hydrodynamic calculation ensues from the well-known boundary value problem for a single-body. The aim is to calculate the velocity potential \( \varphi \) of the fluid.

From the hydrodynamic point of view, the simplest way to consider the case of two bodies is to imagine the single body with 12 degrees of freedom. In this way the generalization becomes straightforward. In fact the potential \( \varphi \) becomes:

\[
\varphi = \varphi_1 + \varphi_D - i \omega \sum_{j=1}^{12} \xi_j \varphi_{Rj}
\]

where

\[
\begin{align*}
\varphi & \quad \text{is the total potential} \\
\varphi_1 & \quad \text{is the incident potential} \\
\omega & \quad \text{is the frequency} \\
\xi_j & \quad \text{is the } j^{th} \text{ body motion}
\end{align*}
\]

As in the case of a single body, the potential \( \varphi_D \) is the perturbation potential when two bodies are fixed while the remaining 12 potentials \( \varphi_{Rj} \) are the radiation potentials corresponding to the movements of the bodies (for example, the potential \( \varphi_{R8} \) is the potential obtained when the second body moves in sway while the first body is fixed.).

The integration of the pressure gives the corresponding hydrodynamic forces ( \( F^{hd} \) )

\[
\{F^{hd}\} = \{F^{DI}\} + (\omega^2 [A] + i \omega [B]) \{\xi\}
\]

where:

\[
F_{ij}^{DI} = i \omega \rho \int_{S_i} (\varphi_i + \varphi_D) n_i dS, \quad i = 1, 6
\]

\[
F_{ij}^{DI} = i \omega \rho \int_{S_i} (\varphi_i + \varphi_D) n_i dS, \quad i = 7, 12
\]

\[
\omega^2 A_{ij} + i \omega B_{ij} = \rho \omega^2 \int_{S_{ij}} \varphi_{Rj} n_i dS, \quad i = 1, 6
\]

\[
\omega^2 A_{ij} + i \omega B_{ij} = \rho \omega^2 \int_{S_{ij}} \varphi_{Rj} n_i dS, \quad i = 7, 12
\]

where \( S^1_B \) and \( S^2_B \) represent the mean surface of the first and the second body, respectively, \( n_i \) for \( i \) from 1 to 6 the normal vector on the first body, \( n_i \) for \( i \) from 7 to 12 the normal vector on the second body, \( [A] \) and \( [B] \) the added mass and the damping matrix for the two bodies.

The final equation of motion takes the same form as in the single body case:
\[
(-\omega^2[M] + [A]) - i\omega[B] + [C])\ddot{\xi} = \{F^{in}\} + \{F^e\}
\]
where:
- \([M]\) is the genuine mass matrix
- \([C]\) is the restoring matrix
- \([F^e]\) are the exterior forces.

All matrices are given for the 12 degrees of freedom including the interaction stiffness in the matrix \([C]\).

The following notations can be introduced:

\[
\begin{align*}
\{F^e\} &= \{F^{e_1}\}, \\
[M] &= \begin{bmatrix} [M]^{11} & 0 \\ 0 & [M]^{22} \end{bmatrix}, \\
[A] &= \begin{bmatrix} [A]^{11} & [A]^{12} \\ [A]^{21} & [A]^{22} \end{bmatrix}, \\
[B] &= \begin{bmatrix} [B]^{11} & [B]^{12} \\ [B]^{21} & [B]^{22} \end{bmatrix}, \\
[C] &= \begin{bmatrix} [C]^{11} & [C]^{12} \\ [C]^{21} & [C]^{22} \end{bmatrix}
\end{align*}
\]

Where 1 or 2 indicate the number of the body and 12 and 21, the interactions between the two bodies.

HYDROSTAR is able to directly calculate the stiffness of the link between the bodies (matrix \([C]^{12}\) and \([C]^{21}\)) for some common type of link.

**Spectral analysis**

Based on the multi-body hydrodynamic calculation, the response spectrum of motions is obtained by the below formula:

\[
R_\phi(H_s,T_z,V,\alpha,\omega) = FT_\phi(V,\alpha,\omega) S(H_s,T_z,\omega)
\]

Where:
- \(R_\phi\) Response spectrum of motion
- \(FT_\phi\) Transfer function of motion
- \(S\) Wave spectrum
- \(H_s\) Significant wave height
- \(T_z\) Zero up crossing period
- \(V\) Ship speed
- \(\alpha\) Heading angle of the ship with respect to incident wave
- \(\omega\) Wave circular frequency.

Short term values considered are \(2V_{1/3}\):

\[
2V_{1/3} = 4\sqrt{M_0},
\]

\[
M_0 = \text{response spectrum area} = \int_0^\infty R_\phi(H_s,T_z,V,\alpha,\omega) \, d\omega
\]

If we consider that the maximum distribution follows a Rayleigh law, the maximum motion on the sea state in a time \(T\) is:

\[
X_{max} = \left[\frac{2 \log \frac{T}{T_z}}{\gamma} + \frac{\gamma}{2 \log \frac{T}{T_z}}\right] \sqrt{M_0}
\]

where:
- \(\gamma\) is the constant of Euler and is equal to 0.5772
- \(T\) is the sea state time (usually 3 hours)
- \(X\) is one of the six degrees of freedom.

**Hydrodynamic Model**

The model was built with 2917 nodes and 2304 panels for the whole model as shown in Figure 2. (1656 panels for the FPSO and 648 panels for the Flotel)

**Irregular wave results**

Spectral analysis has been made using a JONSWAP wave spectrum:

\[
S(\omega) = aH_s^2 \sigma^{4} \omega^{5} e^{-\frac{5}{3} \left(\frac{\omega}{\omega_p}\right)^{-\gamma}} \left(\frac{\omega - \omega_p}{\sigma}\right)^{2}\frac{a^2}{\omega_p^2}
\]

with:
- \(a = e\)
- \(\sigma = \begin{cases} 0.09 & \text{for } \omega > \omega_p \\ 0.07 & \text{for } \omega < \omega_p \end{cases}\)

Where:
- \(H_s\): significant wave height (m)
- \(T_p = \frac{2\pi}{\omega_p}\) is the peak period
- \(\gamma\) parameter of amplification

The coefficient \(a\) is calculated at each step of the computation in order to respect the relation:

\[
H_s^2 = 16 \int_0^\infty S(\omega) \, d\omega
\]

**Results**

The calculations were made for the FPSO alone, the Flotel alone and the two units in presence of each other.
The first results of the computation show that the Flotel does not influence the motions of the FPSO for any wave directions.

But the RAO’s of the Flotel are very influenced by the FPSO especially the pitch motion as we can see in Figure 3, when compared to classic pitch RAO’s for barges.

**Relative motions:**
In order to properly design the gangway, the relative motions for the wave frequencies are to be assessed along the main three axes, for various Hs and Tp.

We studied the relative motions of the two bodies. The point of calculation on the FPSO is x=0 m, y=0 m, z=0 m in the global reference system, and for the Flotel x=-40 m, y=0 m, z=0 m.

The RAO shows that the relative z-motion is important, especially for a wave heading of $\beta = 315^\circ$. The reason is because the motions of the two bodies are not in phase, in fact they are close to be in opposition of phase. In order to reduce this out-of-phase behaviour, it is recommended to vary the distance set between the two floating structures and assess the influence on the vertical relative RAO. Some computations were reperformed by reducing and increasing the distance between the two bodies. 20 m, 30 m, 50 m, 60 m were selected and some results are plotted in Figure 4.

In order to determine the maximum of the motion in a storm of 3 hours we made a short term spectral analysis with the 10 years wave data:
- $H_s = 3.7$ m,
- $T_p = 16.25$ sec.

These wave data are corresponding to the South West wave which is in our case the incidence $315^\circ$. The results are single amplitude results for various distances set between the two structures:

<table>
<thead>
<tr>
<th></th>
<th>20 m</th>
<th>30 m</th>
<th>40 m</th>
<th>50 m</th>
<th>60 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>X motion (m)</td>
<td>3.43</td>
<td>3.03</td>
<td>3.53</td>
<td>3.51</td>
<td>3.41</td>
</tr>
<tr>
<td>Y motion (m)</td>
<td>1.89</td>
<td>2.30</td>
<td>2.08</td>
<td>2.16</td>
<td>2.24</td>
</tr>
<tr>
<td>Z motion (m)</td>
<td>6.58</td>
<td>6.88</td>
<td>7.15</td>
<td>7.38</td>
<td>7.57</td>
</tr>
</tbody>
</table>

We also analyse the influence of the stiffness on the motions of the two bodies. We find that there is no influence of the stiffness (even the stiffness between the FPSO and the Flotel) on the in-plane and out-of-plane motions.

**Accelerations of the two bodies:**
We have also calculated the RAO of the accelerations of the two bodies. Spectral analyses were performed as well and some results are given below. The results are single amplitude results for various distances set between the two structures and for the normal working $H_s$ (2m) and for a wide range of period:

<table>
<thead>
<tr>
<th></th>
<th>20 m</th>
<th>30 m</th>
<th>40 m</th>
<th>50 m</th>
<th>60 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>X acceleration (m/s²)</td>
<td>0.092 (18s)</td>
<td>0.092 (18s)</td>
<td>0.092 (18s)</td>
<td>0.092 (18s)</td>
<td>0.092 (18s)</td>
</tr>
<tr>
<td>Y acceleration (m/s²)</td>
<td>0.38 (11s)</td>
<td>0.38 (11s)</td>
<td>0.38 (11s)</td>
<td>0.38 (11s)</td>
<td>0.38 (11s)</td>
</tr>
<tr>
<td>Z acceleration (m/s²)</td>
<td>0.88 (13s)</td>
<td>0.88 (13s)</td>
<td>0.88 (13s)</td>
<td>0.88 (13s)</td>
<td>0.88 (13s)</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>20 m</th>
<th>30 m</th>
<th>40 m</th>
<th>50 m</th>
<th>60 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>X acceleration (m/s²)</td>
<td>0.37 (11s)</td>
<td>0.36 (11s)</td>
<td>0.35 (12s)</td>
<td>0.34 (12s)</td>
<td>0.33 (12s)</td>
</tr>
<tr>
<td>Y acceleration (m/s²)</td>
<td>0.94 (10s)</td>
<td>0.92 (10s)</td>
<td>0.91 (10s)</td>
<td>0.91 (10s)</td>
<td>0.91 (10s)</td>
</tr>
<tr>
<td>Z acceleration (m/s²)</td>
<td>1.53 (10s)</td>
<td>1.47 (10s)</td>
<td>1.41 (10s)</td>
<td>1.40 (10s)</td>
<td>1.39 (10s)</td>
</tr>
</tbody>
</table>

The maximum vertical acceleration is 1.53 m/s² for the Flotel ($T_p = 10s$) and it does only represent 16% of the acceleration of the gravity.

**Relative motions in the coordinate system of the gangway:**
The new origin of the coordinate system is the point where is connected the gangway on the Flotel. We calculated $r$, the lengthening of the gangway, $\theta$ the azimuth angle and $\phi$ the pitch angle of this gangway.

The gangway is connected at the Flotel at the point (in the two bodies coordinate system):
- $X = -40$ m (for the case distance 40 m)
- $Y = 0$ m
- $Z = 0$ m.

It is also connected at the FPSO at the point (in the two bodies coordinate system):
- $X = 0$ m
- $Y = 0$ m
- $Z = 0$ m.

The method used to calculate this data is:

$$ r(t) = \sqrt{(D + X(t))^2 + Y(t)^2 + Z(t)^2} - D $$

with: $D$ : The distance between the FPSO and the Flotel,
\[ X(t) = X_R \cos(\omega t) + X_I \sin(\omega t) \]
The complex form of the horizontal relative motion,
\[ Y(t) = Y_R \cos(\omega t) + Y_I \sin(\omega t) \]
The complex form of the transversal relative motion,
\[ Z(t) = Z_R \cos(\omega t) + Z_I \sin(\omega t) \]
The complex form of the vertical relative motion.

So the pseudo transfer function is:
\[ r = \frac{1}{2} [r_{\text{max}}(t) - r_{\text{min}}(t)] \]

For \( \theta \) the calculation was:
\[ \theta = \tan^{-1}\left( \frac{Y}{D + X} \right) \approx \frac{Y}{D} \quad \text{because } D \gg X \]

And for \( \phi \):
\[ \phi = \tan^{-1}\left( \frac{Z}{\sqrt{(D + X)^2 + Y^2}} \right) \approx \frac{Z}{D} \quad \text{because } D \gg X \]

and \( D \gg Y \).

For various distances between the two floaters and for the normal working \( H_s (2m) \) and for various \( T_p \), the results are as follow:

<table>
<thead>
<tr>
<th>r (m)</th>
<th>20 m</th>
<th>30 m</th>
<th>40 m</th>
<th>50 m</th>
<th>60 m</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \theta ) (deg)</td>
<td>5.15 (12s)</td>
<td>4.20 (12s)</td>
<td>3.14 (12s)</td>
<td>2.55 (12s)</td>
<td>2.18 (12s)</td>
</tr>
<tr>
<td>( \phi ) (deg)</td>
<td>14.4 (12s)</td>
<td>9.75 (12s)</td>
<td>7.45 (12s)</td>
<td>6.01 (12s)</td>
<td>5.00 (12s)</td>
</tr>
</tbody>
</table>

We also calculate the pitch and the yaw angle between the FPSO and the waterline and between the Flotel and the waterline. (For \( D=40m \))

**Other configuration**
In this configuration the distance between the FPSO and the Flotel is 30 meters but the point where the gangway is put on the Flotel is 20 meters behind the edge of it. The given results are for \( H_s=3.7m \).

Relative motions
- in \( X \) : 2.94 m,
- in \( Y \) : 1.92 m,
- in \( Z \) : 6.61 m.

The angles between the two bodies and the waterline have been calculated as well.

For angles between the FPSO and the waterline:
Azimuth (deg) =2.92

Pitch angle (deg) =6.5

For angles between the Flotel and the waterline:
Azimuth (deg) =2.76
Pitch angle (deg) =4.07

Lengthening and angle:
- \( r = 3.67 \) m
- \( \theta = 3.59 \) deg
- \( \varphi = 7.78 \) deg

**Fully loaded case:**
The distance between the Flotel and the FPSO is 40 meters.
The FPSO was taken with a trim which is the real trim observed on the site. Drafts are:
- fore draft: 23.7 m,
- aft draft: 20.7 m.

Relative motions:
The results following are the maximum value for relative motions in single amplitude.
For 10 years conditions, \( H_s = 3.7 \) m, \( T_p = 16.25 \) s and wave heading is SW (inc = 337.5°).
- \( X = 2.6 \) m,
- \( Y = 1.80 \) m,
- \( Z = 6.83 \) m.

Lengthening and angle:
- \( r = 2.60 \) m
- \( \theta = 1.96 \) deg
- \( \varphi = 6.90 \) deg

Admissible \( H_s/T_p \) curves
In order to define the limiting weather conditions, admissible \( H_s/T_p \) curves for incidence at +/- 22.50° from head seas (S and SW headings) was determined by satisfying the following criteria (see Figure 5):
- Vertical motion less than +/-3m.
- Vertical acceleration less than 0.15g.

**Conclusions**
It appears that the results typical for the gangway design are similar for various loading conditions. The biggest challenge seems to be to cope with the relative vertical motions, which are induced by the almost opposite-phase motions of the two structures.

**MOORING ANALYSIS**
The purpose of the mooring analysis is to define the minimum and maximum in-plane low frequency motions of the two units under the effect of wind, wave and current. In addition the tensions in the various components of the mooring and anchoring system are to be defined, by combining both the low frequency and wave frequency responses. The methodology to
perform such mooring analysis can be found in Bureau Recommended Practice and other documents [1], [2], [3].

**FLOTTEL Mooring system**

The Flotel will be moored to 6 pre-installed mooring buoys. In addition the Flotel is connected to the FPSO with 4 lines.

<table>
<thead>
<tr>
<th>LINE #</th>
<th>AZIMUTH (deg/N)</th>
<th>PRE TENSION (kN)</th>
<th>FAIRLEAD POSITION (m)</th>
<th>PAID OUT LENGTH (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>341.71</td>
<td>363.</td>
<td>50.0 0. 5.0</td>
<td>47.15</td>
</tr>
<tr>
<td>2</td>
<td>341.71</td>
<td>363.</td>
<td>50.0 0. 5.0</td>
<td>47.15</td>
</tr>
<tr>
<td>3</td>
<td>58.29</td>
<td>363.</td>
<td>50.0 0. 5.0</td>
<td>47.15</td>
</tr>
<tr>
<td>4</td>
<td>58.29</td>
<td>363.</td>
<td>50.0 0. 5.0</td>
<td>47.15</td>
</tr>
</tbody>
</table>

**CONNECTION TO THE FPSO**

<table>
<thead>
<tr>
<th>LINE #</th>
<th>AZIMUTH (deg/N)</th>
<th>PRE TENSION (kN)</th>
<th>FAIRLEAD POSITION (m)</th>
<th>PAID OUT LENGTH (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>243.</td>
<td>253.</td>
<td>-50.0 -15.0 5.0</td>
<td>2337.</td>
</tr>
<tr>
<td>2</td>
<td>238.</td>
<td>253.</td>
<td>-50.0 -15.0 5.0</td>
<td>2337.</td>
</tr>
<tr>
<td>3</td>
<td>162.</td>
<td>253.</td>
<td>-50.0 15.0 5.0</td>
<td>2337.</td>
</tr>
<tr>
<td>4</td>
<td>157.</td>
<td>253.</td>
<td>-50.0 15.0 5.0</td>
<td>2337.</td>
</tr>
<tr>
<td>5</td>
<td>152.</td>
<td>253.</td>
<td>-50.0 15.0 5.0</td>
<td>2337.</td>
</tr>
<tr>
<td>6</td>
<td>248.</td>
<td>253.</td>
<td>-50.0 -15.0 5.0</td>
<td>2337.</td>
</tr>
</tbody>
</table>

**ANCHORING**

For the anchoring, to achieve the pretension, the anchors are to be set at 1695m from the fairlead. In addition the positions of the fairlead on the FPSO side are supposed to be 1365m above seabed or 25m above the FPSO keel.

The breast and cross lines are connected at 2m out from the stern of the FPSO (152m from midship) and +/- 30m from the longitudinal axis.

For such configuration, the Flotel is supposed to be at 40m from the stern of the FPSO when this latter is in ballast condition.

In case of the FPSO being fully loaded (draft = 23.22m), the Flotel is drifting away 2.3m from the FPSO (42.3m total). Therefore the above configuration will be as follows:

<table>
<thead>
<tr>
<th>LINE #</th>
<th>AZIMUTH (deg/N)</th>
<th>PRE TENSION (kN)</th>
<th>FAIRLEAD POSITION (m)</th>
<th>PAID OUT LENGTH (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>343.3</td>
<td>337.</td>
<td>50.0 0. 5.0</td>
<td>47.15</td>
</tr>
<tr>
<td>2</td>
<td>343.3</td>
<td>337.</td>
<td>50.0 0. 5.0</td>
<td>47.15</td>
</tr>
<tr>
<td>3</td>
<td>56.7</td>
<td>337.</td>
<td>50.0 0. 5.0</td>
<td>47.15</td>
</tr>
<tr>
<td>4</td>
<td>56.7</td>
<td>337.</td>
<td>50.0 0. 5.0</td>
<td>47.15</td>
</tr>
</tbody>
</table>

**CONNECTION TO THE FPSO**

<table>
<thead>
<tr>
<th>LINE #</th>
<th>AZIMUTH (deg/N)</th>
<th>PRE TENSION (kN)</th>
<th>FAIRLEAD POSITION (m)</th>
<th>PAID OUT LENGTH (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>243.1</td>
<td>250.</td>
<td>-50.0 -15.0 5.0</td>
<td>2337.</td>
</tr>
<tr>
<td>2</td>
<td>238.</td>
<td>250.</td>
<td>-50.0 -15.0 5.0</td>
<td>2337.</td>
</tr>
<tr>
<td>3</td>
<td>162.</td>
<td>250.</td>
<td>-50.0 15.0 5.0</td>
<td>2337.</td>
</tr>
<tr>
<td>4</td>
<td>156.9</td>
<td>250.</td>
<td>-50.0 15.0 5.0</td>
<td>2337.</td>
</tr>
<tr>
<td>5</td>
<td>151.9</td>
<td>250.</td>
<td>-50.0 15.0 5.0</td>
<td>2337.</td>
</tr>
<tr>
<td>6</td>
<td>248.1</td>
<td>250.</td>
<td>-50.0 -15.0 5.0</td>
<td>2337.</td>
</tr>
</tbody>
</table>

No dynamic winching has been implemented in our calculations.

The properties of the mooring system are as follow:

<table>
<thead>
<tr>
<th>CONNECTION TO THE FPSO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
</tr>
<tr>
<td>Segment 1</td>
</tr>
<tr>
<td>Segment 2</td>
</tr>
<tr>
<td>Segment 3</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>ANCHORING</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
</tr>
<tr>
<td>Segment 1</td>
</tr>
<tr>
<td>Segment 2</td>
</tr>
<tr>
<td>Segment 3</td>
</tr>
<tr>
<td>Segment 4</td>
</tr>
</tbody>
</table>

At the end of Segment 3 is a mooring buoy connected, the properties of which are as follow:

| Buoyancy: | 630 kN |
| Weight: | 10 kN |
| Height: | 2 m |

The properties of the Nylon segment are coming from Marlow catalogue.

Regarding load-extension characteristics for the Nylon segment, the curve corresponding to a ‘worked Superline rope’ (Marlow data) has been conservatively assumed (the stiffest).

In addition, in ARIANE, a fifth-order polynom is assumed to represent the non-linear elastic properties.

Meanwhile for comparison purposes, at certain stages of the analysis we have implemented another type of Nylon rope such as ‘Marlow Braidline’ in worked condition, which is more elastic than the “Superline”.
Equilibrium of the whole system - barge Flotel

The Flotel is set at 40.0m from the FPSO in order to achieve a general equilibrium without external load.

For the mooring analysis, the origin of the global axis system is set at the free surface on the stern of the FPSO at the longitudinal axis system. The OX axis is positive forward and OY axis is negative rightward (see figure 1).

Acceptance criteria

The criterion used for the maximum allowable design tension is as follows:

- Safety factor of 1.75 in Intact condition for the mooring lines of the FPSO.
- Safety factor of 1.25 in damage condition for the mooring lines of the FPSO.
- Safety factor of 2.20 in Intact condition for the anchoring and connections of the FLOTEL as their damage may induce the Flotel to be in contact with the FPSO.
- Safety factor of 1.75 in Damage condition for the anchoring and connections of the FLOTEL.
- The Flotel shall not be in contact with the FPSO at any time. Furthermore a safety zone of 10m minimum shall be kept between the two structures at any time.

Potential Feasible Flotel mooring system

The proposed mooring system fit the various imposed requirement and can be summarised by the following:

<table>
<thead>
<tr>
<th>Intact</th>
<th>1Y Achieved SF / Ref. SF</th>
<th>10Y Achieved SF / Ref. SF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hawser design tension</td>
<td>1400 kN</td>
<td>2.5 / 2.2</td>
</tr>
</tbody>
</table>

Anchoring design tension 380 kN 7.11 / 2.2 410 kN 6.59 / 2.2

The above proposed tensions are for the complete response of the system, including wind, current, slow drift effects with the first-order wave motions.

The proposed tensions are for individual hawser/segment and not for a system of double hawser.

For such analysis and for the Ballast FPSO, it has been found that we still have a safety factor of 2.2 in 10Y weather conditions for the "Worked Superline". In addition for the ‘Worked Superline’, the obtained safety factor is around 2.6 for the same weather and FPSO configuration.

Typically for the "Worked Superline" hawser in 10Y condition, the safety factor of 2.2 is decomposed as follow:

- Equilibrium Tension (under mean effect of wind, wave-slow drift and current) : 441.5 kN
- Low frequency tension (under effect of wind, wave-slow drift and current): 550. KN
- Low+wave frequency tension (under effect of wind, wave-slow drift, wave first-order motion and current ) : 1590kN

It is to be noted that such decomposition may vary according each weather condition.

Furthermore, when the FPSO is in fully loaded condition, we obtained a safety factor of 2.6 in 10Y weather conditions for the "Worked Superline".

Gangway In-Plane design

The results are for the mean effect of wind and current and slow drift. Pt1 corresponds to Alternative 1 and Pt 2 to Alternative 2.

The plotted values are absolute, e.g. it is the minimum and maximum distance between the two contact points of the gangway projected in the global axis system.

For the Low frequency response only of the Flotel (FPSO fixed) and for the 10Y weather conditions, the extreme values of D1 & D2 are as follow :
D1 : Distance between Pt1 & Pt1bis
D2 : Distance between PT2 & Pt2bis
Intact - D1 max= 41.2m / D2 max= 52.5m
Damage - D1 max= 40.7m / D2 max= 54.6m

Anchor & Buoy design

At the anchor & buoy side, the results in intact with the first order wave effects (low+wave frequency) can be summarised as follow:

Intact 10Y – Tension at the fairlead : 410. kN
Intact 10Y - Tension at the anchor : 430. kN
Intact 10Y - Angle at the anchor point : 18.7 deg
Intact 10Y - Tension at the buoy : 719. kN
Damage 10Y – Tension at the fairlead : 460. kN
Damage 10Y - Tension at the anchor : 483.1 kN
Damage 10Y - Angle at the anchor point : 20.0 deg
Damage 10Y - Tension at the buoy : 768. kN

**Hawser Fatigue**
As the synthetic hawser between the two floating structures may be the critical items, it should be therefore necessary to check the fatigue life of such components. A fatigue analysis should be implemented for the various weather conditions to be encountered during the project life. Therefore, the number of tension cycles should be recorded on typical Rainflow methodology (or others) and weighted by the appropriate probability of occurrence. One of the difficulties should be to characterize the fatigue properties of such synthetic hawser and assessment by specialised laboratories may be requested.

**Hawser slack risk**
In order to ensure that the hawser will not induce any compression or at very low level, it is therefore necessary to assess the minimum tension and their occurrence for the various weather conditions to be encountered during the project life. The targeted minimum tension should be the weight of the hawser. In our case, the minimum tension is always greater than the weight of the hawser, therefore no risk of compression.

**Operational issues**
From an operational perspective, it should also be necessary to assess the ability of the Flotel to move away from the FPSO in case of emergency on one of the two structures. A drifting analysis could be performed using mooring analysis software as follow:

For the drifting analysis, the hawsers have been released all together at the same time in order to appraise the minimum distance between the FPSO stern and the Flotel which can be achieved passively. In order to properly analyse such effect, several weather conditions have been applied mainly from South (e.g. weather conditions pushing the Flotel towards the FPSO). In addition the damping of the unit has been increased in order to deal the extra amount of damping when the lines are slackening and to allow a certain level of conservatism.

For the 1Y weather conditions, when the connections are released, the Flotel can reach a position of 175m away from the FPSO without human intervention in all the cases. This 175m margin should be attained within 500s.

Furthermore, the 500m safe distance is reached without Human intervention for all the weather conditions. See figures 7 for the critical weather pattern from the south.

**RECOMMENDATIONS & CONCLUSION**
The design of connection(s) between two floating bodies shall be based on state-of-the-art hydrodynamic and mooring analyses, with the following specificities:
- Capacity to perform hydrodynamic computation integrating screen effect for the 1st order 6 d.o.f. motions of the two structures in order to well model the potential out-of-phase motions of the two bodies,
- Capacity to perform multi-body mooring analysis with multiple connections between vessels and with seabed, in order to deal with dynamic response of the system.

In addition the following topics specific to the project but also relevant for others, have been raised and should be carefully reviewed:

1. The design of the anchors shall allow permanent vertical pull. Furthermore, because of the potential position of the Flotel (after drifting induced by release) over and behind the anchors, these latter should allow such configuration, which may trigger re-testing.

2. It has been demonstrated that according the considered Nylon construction, the achieved safety factor can improve.

3. Fatigue lives of the short synthetic connections may be the critical point of the Flotel concept and therefore should be properly assessed.

4. When the supplier of the hawser will be selected, the proper properties including elastic ones, will need to be fully considered.

5. It is advised that when the final design of the barge and of the gangway system is set, it will be necessary to check the assumptions of non-screen effect used in the calculations for the wind and current description, despite its conservatism.

6. For the relative out-of-plane motions in phase or out of phase, the swell is the main factor and therefore should be well accounted for in order to properly assessed the limits of the proposed system.

7. It is necessary to ensure on both vessels (FPSO & Flotel) that super-structures will not interfere with the proposed clearance and with the gangway excursions around the connections on both the FPSO and Flotel.
8. Furthermore, as the Flotel system is mainly sensitive to wind & current effect, it is advised to get the proper wind & current coefficients for the selected Flotel for further analysis.

9. During the design stage of the system, it is advised to reassess the clearances of the Flotel system with any other present – and future – structures (subsea development, pipelines layout, etc.) In addition the Flotel and its mooring system should interfere as less as possible with any operational duties.

10. Because of the settings of the hawsers connection between the FPSO and the Flotel, there are risk of damage induced by friction in-between the segments. This potential hazard should be addressed.

11. Dynamic winching may allow to keep the Flotel at the right distance from the FPSO.

Finally, the present report does not deal with the breaking of one of the hawsers. Meanwhile, in case of one breaking segment, it is necessary to avoid tension built-up in the remaining segments. Therefore it may be advised to set one (or two) loose wire rope(s) in case of damage, either parallel to the present settings or straight from the FPSO to the Flotel. The length of such wire rope(s) should be selected in such a way to tackle remaining hawsers excessive elongation after damage.

It has been showed that in all the cases the 10m safe margin between the two units is fully respected, even in damage cases.

ACKNOWLEDGMENTS
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REFERENCES
1. Bureau Veritas NR 493.


Figure 1: Settings of the system
Figure 2: Hydrodynamic meshes

Figure 3: Flotel Pitch RAO’s influenced by FPSO
Figures 4: Various distance Z responses
Figures 5: Hs / Tp acceptance curves

Distance between Flotel and FPSO sterns - 1Y weather condition

Figure 6: Flotel drifting for the 1Y conditions
Figure 7: Flotel drifting for the 10Y conditions