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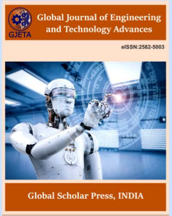

(RESEARCH ARTICLE)

Analysis of FPSO station keeping characteristics

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Abstract

Nowadays with increasing production and exploration activities offshore, the FPSO system has been widely adopted globally because of its unique design system and adaptability to these offshore environmental conditions. This research project aims to provide the station-keeping characteristics of an FPSO in the West African region, by analysing an FPSO with spread mooring design for multiple load cases, different offset, multiple draught conditions and environmental loads, all acting simultaneously and dynamically on the coupled FPSO system. Static and dynamic analysis were conducted using the Orcaflex software to establish the station-keeping characteristics, the recommended practices by DNV for mooring and global performance analysis were utilized for the mooring lines in the static analysis to obtain the primary equilibrium position before the dynamic analysis was conducted and to estimate a dynamic response of the risers in dynamic analysis.

The effective tension of the static and dynamic analysis results for the different draught and environmental conditions shows that the far offset had the maximum effective tension, with the fully laden effective tension been the maximum effective tension of the entire simulation. The increase in effective tension as the loading of the FPSO tanks increased caused a reduction in the bending moment radius and thereby reducing the curvature of mooring lines and riser bends. But it was the near offsets that had the minimum bending radii as expected, however, from the analysis the draught conditions provided the largest responses to the multiple loading cases when compared with the changes in the offset positions.

Keywords: Floating Production Storage and Offloading system (FPSO); Effective Tension; Mooring system of FPSO; Maximum Bending Moment; Orcaflex

1. Introduction

A Floating offshore structure must have station-keeping capability for efficient Productivity. The position of an FPSO offset is typical 8% of water depth and a 10% for damaged conditions, Turret systems commonly are installed in severe environmental conditions to allow the FPSO weathervane. In the Arctic region, the ice induced load must be considered in the design of a station-keeping system [1]. Station-keeping systems for a floating structure can be either spread mooring, single point mooring or Dynamic-positioning (DP). A typical Spread mooring consist of a group of mooring lines terminated at the corners of the vessel, for example the FPSO Bonga to hold it stable in the heading direction. As oil production moves into harsh environments and Deepwater in the bid to meet the world energy demands. New technological advancement is being adopted to optimize production in an eco-friendlier way. For a Floating offshore system with station keeping as one of its major components, a more consistent understanding of the hydrodynamic

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interaction between the mooring lines, the risers and the cylindrical hull in a dynamic system will be very important giving the complex nature of it. A better and a more consistent understanding of the characteristics associated with station keeping in a particular location is vital, in this case West Africa (Gulf Guinea), hence, advance methodologies are needed to provide a much deeper understanding of the system behaviour. Efficient tools and procedures on how to determine how the FPSO response to the environmental loads it encounters will be needed.

The powerful floating structures used for petroleum activities are maintained on station for a very long time by multiple mooring line systems. Centuries now, there has been the system of a single anchor mooring system from the bow [2]. The mooring is the station-keeping system referred to in this design in this research. In the year's past, the experience developed of ship building and offshore structures has aided engineering operators of mooring design [3].

One of the main purpose of the mooring system in an FPSO is to allow the relative movement of the FPSO according to external loads (environmental loads), in-site ensuring that the FPSO remains close to the point it was originally designed for, since both structural and functional inadequacy affects also the efficiency of energy conversion used in station keeping and offshore operations [4]. Two common types of mooring systems are extensively used which spread mooring and single point are mooring with turret. Turret systems commonly are installed in severe environments. In the Arctic region, the ice induced load must be considered in designing a station-keeping system [5]. The mooring lines are an important component in station keeping, they are either made of chain, rope or synthetic fibre, sometimes a combination of all three. Segmented mooring lines, having heavy chain at the bottom and a lighter line close to the surface, allows for greater stiffness and lighter mooring lines [6].

Ansari 1980 conducted an extensive study of mooring systems with a multi-component mooring line system. The study presented a broad description of the various mooring lines usually available for use and presented an analysis tool in determining the effect of line stretch and the stiffness characteristics of a multi-component line system [7]. In 1991 he also presented a study on the design of multicomponent cable systems for a moored offshore vessel. The study presented the equations of motion of a moored vessel and methods of generating the restoring force. The study stated the importance of having the dynamic effects and added mass in the dynamics of the vessel when analysis is being carried out [8].

Macfarlane in 2001 conducted a study on the statics of a three-component mooring line. The study adopted the configuration of a deep water mooring which was connected to a floating platform that is moored needed for the preliminary mooring systems design. The study concluded that to minimize the errors in measurement, that the stability measurement should be used, [9]. Gobat and Grosenbaugh in 2001 conducted a study, for heave induced dynamic tension in catenary mooring lines and he presented an empirical model for it. The model can be applied for wave frequency, with the standard deviation of the tension and the drag term calculated for, the standard deviation was given as the sum of an inertia proportional to heave acceleration [10].

Pacheco, Kenedi, and Jorge in 2002 did a study on the elastoplastic analysis of chain links residual stress. The study describes the effect of residual stress along the links in chain during and after operations, which is important in the fatigue life of a mooring chains, [11]. Ong and Pellegrino in 2003 conducted a study of analysis in the frequency domain on the modeling of seabed interaction of mooring lines. The result of this study describes how the accuracy in the analysis of frequency domain modeling of the interaction with the seabed is more precise than the conventional analysis, [12].

Pacheco et, al, in 2003 conducted a comparative study on the distribution of stress prediction in stud-less chain links, FEM was adopted to analysis residual stress applied to offshore stud-less chain links and came up with tow phenomena that affected stress prediction which are plasticity and contact, [13]. Vargas et, al, performed a study on the stress concentration factors for stud-less mooring rope links in the fairleads. The study analyzed the stress concentration factors on seven (7) pocket fairleads, showing a maximum stress concentration less than 1.20, [14].

Ridge et, al, in 2006 conducted a study to predict methodologically the torsional response in large mooring systems. The torque and the end shortening of the mooring chain were predicted with a frictionless theory as a function of the twist angles. During the study, the results obtained were compared to experimental data, and design curves were obtained to enable designers in the estimation end shortening and torque for bar diameter, [15].

Yassir, Kurian, and Nabilah in 2010 conducted study on the multi component catenary mooring line for an offshore floating system, the study was a parametric study that utilized an implicit iterative solution, for the multi component catenary system using equations. The study conducted established that restoring force (horizontal)is proportional to the unit weight parameter and pretension, and for positive excursion, it is inversely proportional to the pretension angle, while the vertical restoring force is proportional to the vertical pretension, [16].

Kiecke in 2012 carried out a study to simulate the fatigue damage index of a mooring chain of a Gulf of Mexico truss spar that was determined from field data records. By utilizing a monitoring system of environmental platform response, the study established that the total fatigue damage caused within a 20-year service life is less than the fatigue damage caused by hurricanes, so therefore the study recommended that a 100-year hurricane should be considered when designing systems for station keeping in line with the Norsok, [17]. The arrangement of the BONGA FPSO in general applies 3 lines in a group of 4 bundle to the hull of the FPSO and 3 lines in bundle of 3 for the SPM buoy with an angle of 120 degrees from each other for station keeping, [18].

This current research study focuses on the response behaviour and the basic characteristics of a typical FPSO in the Western African region, a study that is both extensive and comprehensive in determining and describing the global performance of an FPSO for coupled system (FPSO, mooring and riser system) for different loading conditions in a site-specific location, taking Nigerian environmental data as study focus.

Safety is always a primary concern for an FPSO, as the process of oil recovery is a high-risk activity. Therefore, FPSO motions must be kept below some practical limits, as it directly affects safety standards and level of workability which then leads to increase in cost of design, so a better understanding of the characteristics which leads to these motions is vital. This study will aid this by providing a more consistent understanding of the station keeping characteristics associated with the West African region for better evaluation of FPSO performance. This current research will describe and create a more comprehensive understanding associated with FPSOs and the environmental conditions for the West African region given different limit state, loading conditions and different motions of the FPSO.

2. Material and methods

The analysis of this research made use of the Orcaflex software tool in conducting both static and dynamic analysis of a typical FPSO. The analysis for this research will be guided by the API recommended practise 2SK detailed for design and analysis of the station-keeping systems for offshore floating structures, and the recommended practice of the DNVGL-OS-E301, for position mooring design and the DNV-RP-C205, for environmental conditions, will be used when conducting analysis and modelling in the Orcaflex software.

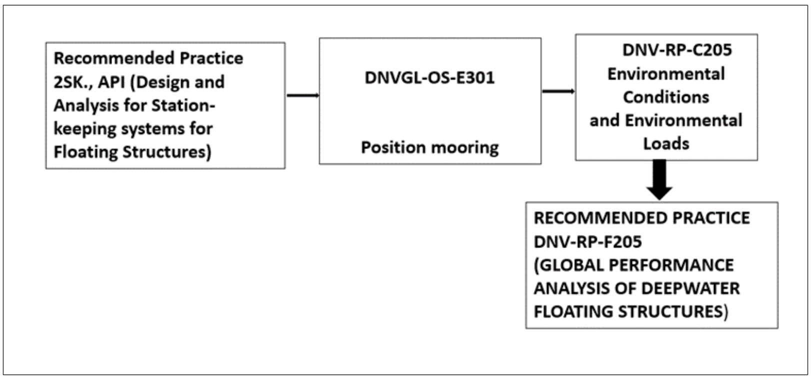

Figure 1 An illustrative overview of standards utilized for this research

Table 1 FPSO and Mooring Lines Data

Length of FPSO	300 meters
Length of Mooring Line	2000 meters
Temperature of Sea	10 °C
Water Depth	1000 meters depth
Number of Mooring Lines	12 mooring lines
Riser Configuration	6"&8"

The above workflow in figure 1 shows how each recommended practice was integrated into this research, for example the DNV-RP-C205 will be utilized for the wave, wind and current loads for the Nigerian sea and the DNV-0S-E301 utilized for the design recommendations of position mooring.

Table 2 Waves (100-year return period)

Associated with Swell	18.0 m/s
Associated with Squall	30.5 m/s

Table 3 Wind (100-year return period)

Nigeria	Hs	Tp
Swell	3.8	15.0
Squall	2.5	7.2

The Orcaflex software will be used for conducting the station-keeping analysis taking the West African (Nigerian) offshore environmental conditions for spread mooring and their responses to the different characteristics and environmental conditions suitable for station-keeping will be compared.

A simple simulation workflow is represented figure 2 below, however the simulation analysis performed for this research work is not limited only to the workflow illustrated in this figure.

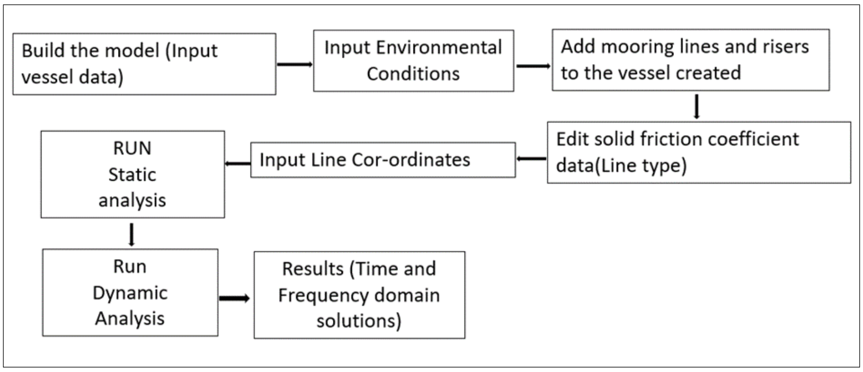

Figure 2 Orcaflex Simulation Workflow

3. Results and discussion

The loading caused by FPSO motions, draught, and offsets as source of load for both static and dynamic conditions is vital when analysing the station keeping characteristics of an FPSO. Static analysis is the prerequisite before dynamic analysis when performing global analysis of an FPSO, it helps to determine the suitable static equilibrium and position for the FPSO under multiple static loads such as vessel offsets, current, gravity, draught, buoyancy, etc. A matrix for different loading cases is presented below in table 4.

For this research static analysis will be conducted for ballast, mid-laden, and fully laden draught conditions and for both operational and accidental conditions for the different offsets (nominal, far, and near).

The results that will analysed to show the FPSO response description are the effective tension, bending moment, curvature, spectral density, extreme value statistics and bending radius.

The effective tension for ballast condition of the FPSO as simulated by Orcaflex for static analysis showed below in figure 3.

From the range of graph presented above the ballast condition shows an effective tension of 918 KN for the near offset in all the different environmental conditions, an effective tension of 920 KN for the nominal offset and 923 KN for the far offset. Accordingly, FPSO far offset gives the highest effective tension for the ballast condition because of the slight extension in the length of the wire rope.

Table 4 Loading Cases

Loading Cases	FPSO Offset	Conditions	Wave and Current Return Periods
1	Nominal	Operational Condition: Intact mooring system for the various draughts and FPSO offset of 10% of the sea depth.	100- year wave period and 10-year current period
2	Far(+34)		
3	Near(-34)		
4	Far(+36.48)	Accidental Condition: Single mooring line damage with 12% sea depth as the offset range	
5	Near(-36.48)		

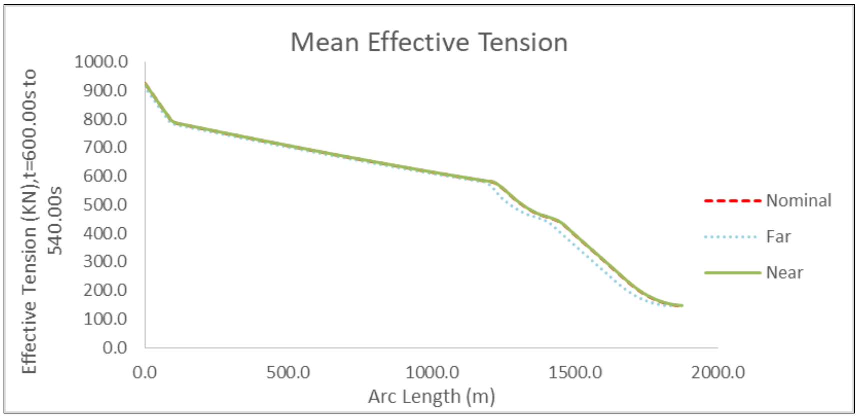

Figure 3 Ballast Static Effective Tension

Bending Moment: Given the bending moment is inversely proportional to the radius of curvature, for the near offset loading scenarios, the distance of the FPSO mooring line to the anchorage is at its closest point, which results in the smallest hog bend and sag bend in radii, when compared to the other offset conditions for the ballast condition, as shown in figure 3.

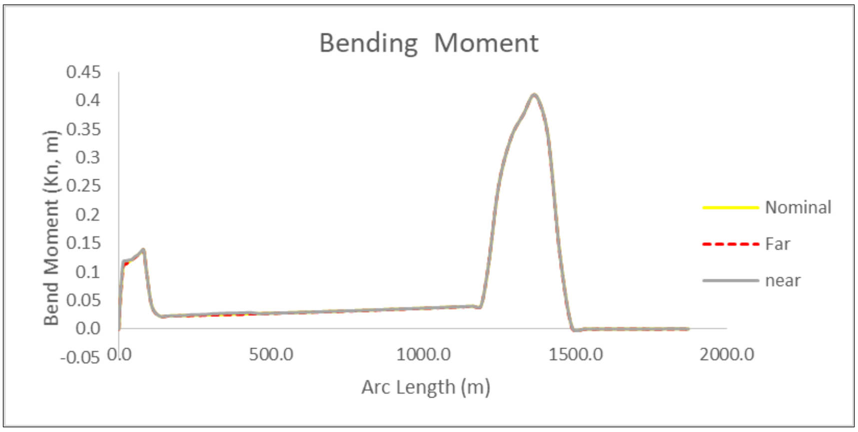

Figure 4 Ballast Static Bending Moment

Although the trend in the graph shows very little difference for the various offsets, which is as a result of how small the difference in the hog radii at the beginning of the mooring line (fairlead) is. The hog bend that occurs from the 1191 meters mark of the mooring line can clearly be seen in figure 4. this hog bend is formed between 1191 meters and 1491 meters for the near offset.

The effective tension for mid laden condition for the static analysis shows a significant average increase for minimum and maximum effective tension, as shown in figure 7 below, the effective tension shows an increase from its ballast condition, with the far offset having the maximum effective tension of 932 KN as can be seen in figure 5 below.

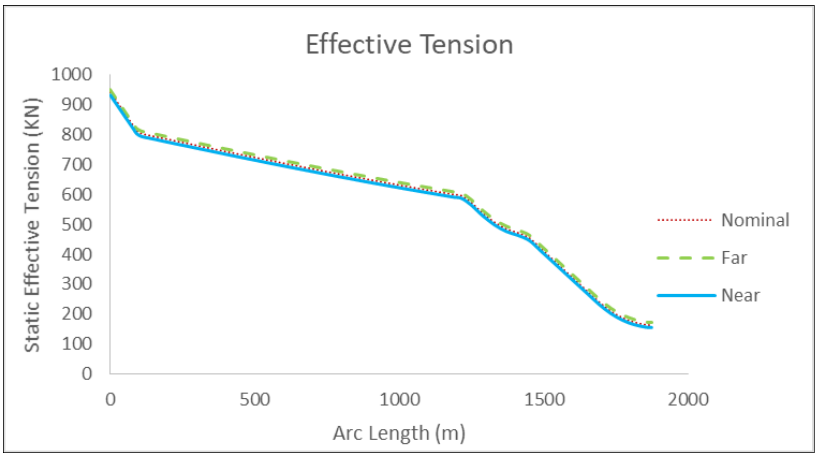

Figure 5 Mid Laden Static Effective Tension

Although the offsets of the FPSO does not significantly affect the tension in the mooring lines, given that it mooring tension is a function of length and for this study a large significant allowance was given to the mooring lines and risers, to reduce tension and fatigue. The slight difference in effective tension for the different offset conditions can also be seen in figure 7 above. The loading condition for the fully laden FPSO was simulated and static analysis conducted in order to describe how the FPSO and mooring configuration will response when the vessel is filled. From the figure 8 below it can be observed that the effective tension for the full laden FPSO has the highest effective tension.

The static analysis for the global performance of an FPSO in the Western African region given the mooring line and riser configuration used in this research clearly shows that the draught condition among other loading cases have the greatest impact on the FPSO response system as shown in the summary table 4.2 below, when compared to the Offset of the FPSO which is a 10% of the water depth and in this case (+34m and -34m).

And from the figure 8 below it can clearly be seen that the fully laden draught condition has the highest effective tension compared to the ballast with the least effective tension. For the bending moment and curvature, the near offset showed the minimum bending moment for the different draught conditions.

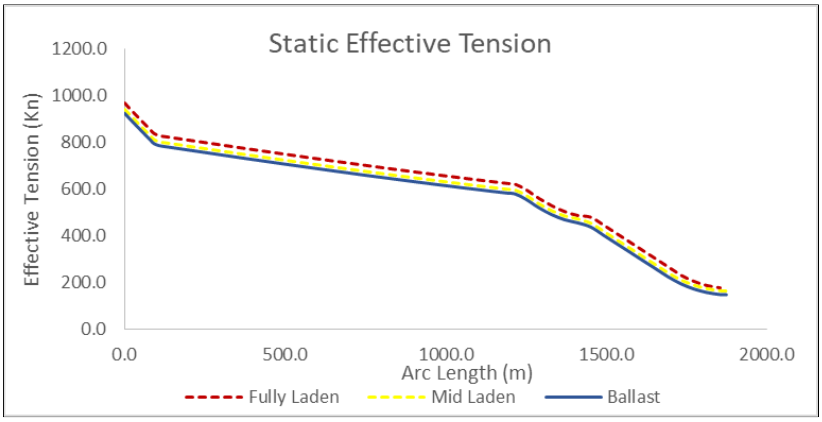

Figure 8 Summary of the Static results

This is the next stage of global performance analysis on Orcaflex and core objective for conducting a dynamic analysis is to estimate and describes the extreme riser system response against a combination of loading forces, during the FPSO service life. Results for the dynamic analysis of the FPSO ballast draught condition for a 100-year wave period and 10-year current period as environmental condition is described for effective tension, bending moment.

The effective tension of the riser system shows a different shape from the mooring systems in the static analysis with even a higher effective tension value as shown in the figure 9 below. But given that the length of the risers is way higher than mooring lines the change in offset point can clearly be seen to having no effect on the riser's response, so the effective tension is 1766 (KN).

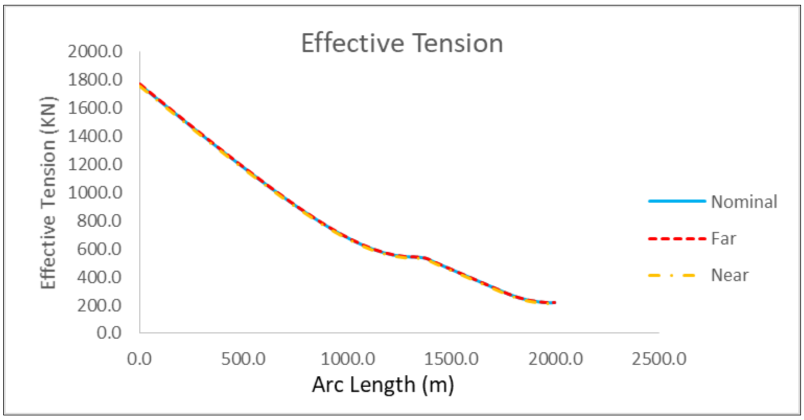

Figure 9 Dynamic Ballast Effective Tension

The dynamic analysis for the fully laden draught condition of the FPSO responses were estimated for a combination of load cases. This fully laden FPSO responses be then compared with that of ballast and mid laden since the offset range produces very small significant response from the coupled system of FPSO, mooring and risers, as had been observed previously. From the range graph of effective tension in figure 10 below, the effective tension for the fully laden FPSO loading condition is the highest effective tension the risers where subjected to, which directly affects the bending radius and curvature.

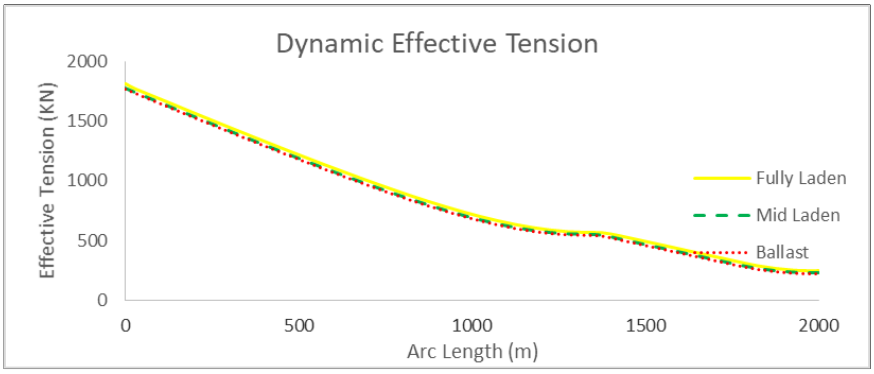

Figure 10 Dynamic Effective Tension for Fully Laden

The maximum effective tension for the riser after dynamic analysis is the fully laden far offset load case as summarized in the table 5, exactly as the static case.

Table 5 Summary of Results

Parameters	Ballast	Mid-Laden	Fully Laden
Max Top Tension (KN)	1766.468	1776.473	1813.2560
Tension at Touchdown point (KN)	219.232	228.854	248.734
Max. Von Mises Stress (Kpa)	91209.093	92348.268	93359.331
Shear Force	219.232	232.476	255.090

The main purpose of global analysis on the coupled system of FPSO, mooring and riser system is to capture a more realistic and comprehensive station keeping response estimate.

4. Conclusion

From the static and dynamic analysis conducted for both ultimate limit state (intact condition) and accidental limit state (damaged condition), the fully laden condition FPSO condition has the maximum effective tension. Because of the large extension in the length of the mooring chains and risers compared to the depth of the sea, the offset positions for the different load cases had little or no significant impact on the response of the overall system. But the large arc length of the mooring and risers were adopted to reduce any form of frequent lateral movement or effective tension.

The FPSO response predictions gotten from the Orcaflex software shows high rate of accuracy, because of the nonlinear coupled static and dynamic analysis conducted, that ensured a more comprehensively integrated system of results and not only provided single responses of each of the systems, mooring risers, and FPSO for different loading conditions and different offset position for both ultimate and accidental limit state conditions. The analysis also provided a coupled dynamic result of the FPSO elements and the slender member (moorings and risers)**,** based on the results from the simulation for the static condition the FPSO has a great stability as there was no buckling or line damage as a result of excessive effective tension.

Compliance with ethical standards

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Disclosure of conflict of interest

All authors would like to declare that there is no conflict of interest relevant to this article.

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