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Numerical Studies on the Effects of Mooring Configuration and line Diameter on the Restoring Behaviour of a Turret- Moored FPSO

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Abstract - Restoring behaviour of a mooring system is majorly dictated by several factors including, pretension, mooring line material, azimuth angle, mooring line diameter and fairlead angle. Mooring line behaviour plays significant role in controlling the dynamic motions of floating offshore platforms. Hence, studying the parameters affecting mooring line responses is a very important aspect in the hydrodynamic analysis of FPSO. The primary aim of this paper is to investigate the influence of mooring line configurations in different wave headings and mooring line diameter on the restoring behaviour of a Turret-Moored FPSO. Force-excursion relationship of the mooring system is determined using an in-house developed MATLAB code, named MLQSC. Catenary mooring line was adopted in the study, consisting of Chain-Steel wire-Chain, and analyse using Quasi static analysis approach. Four (4) mooring configurations considered are Evenly distributed, 3x4, 4x3 and 6x2 in all cases with respect to 30,35,40 and 45-degree wave headings. The restoring behaviour of mooring configurations considered (consisting of 12 mooring lines) was observed to decrease with an increasing wave heading. Furthermore, the restoring behaviour was observed to decrease with increase in mooring line diameter which by implication increases the corresponding permissible excursion.

Keywords: Restoring Forces, Excursion, Mooring configuration, Mooring line Diameter, Turret moored FPSO

1. Background

The dynamic responses of FPSOs to environmental loadings are to a large extent dependent upon structural characteristics of their mooring system [1]. However, for the mutually efficient performance of the integrated system, particularly the mooring lines will depend on factors like floating vessel size, mooring line components, environmental condition and of course, the operational water depth[2], thus the need for diligent analysis of factors influencing the behaviour of mooring lines.

FPSOs are commonly moored using catenary mooring lines to ensure platform operation within safe excursion limit is maintained, usually within 5% to 6% of the water depth [3] relative to the point of riser connection to wellhead during operations [4]. Multi-component mooring lines are mostly used because of their advantage in terms of flexibility and increased stiffness [5, 6]. The geometrical change of mooring line during operation is normally induced by horizontal displacement of the attached platform. Hence, geometrical nonlinearity is reported to have a significant structural influence on mooring line behaviour[7].

Mooring line analysis is majorly carried out using Quasi-static and dynamic analysis. The former has for many years been recommended and used at preliminary design stage [8] to particularly include mooring line effects (restoring force) in the analysis of moored floating platforms. Based on the recommendation given in API RP 2SK [4] only horizontal displacement (surge) of the platform is considered. It is important to note that the surge response is dependent primarily upon both stiffness and magnitude of the externally applied force.

Horizontal restoring forces generated by mooring lines are known to govern FPSO surge and sway natural frequencies as well as the damping to slow drift motions [9]. Thus, in quasi-static analysis, mooring line contribution in the platform motion analysis is normally incorporated as a static modification to the hydrostatic stiffness matrix. Thus, the nonlinearity of the mooring line restoring force due to time-dependent changes in displacement and orientation of the vessel is accounted for using the mooring stiffness matrix. The mooring restoring behaviour is however known to be influenced by several factors, including mooring configuration, line pretension, mooring line material, and diameter and fairlead elevation.

Many studies investigating this parameter have been presented, For example, on the influence of Pretension on restoring behaviour of moorings in Truss Spar [10], mooring line configuration have also been investigated for truss spar[11] and Wave Energy Converter [12], a detailed study on mooring line material [13], mooring line diameter [14], a similar study on properties and fairlead slope in [15].

Despite the reasonable number of investigations available on some of the parameters, few are available on FPSOs. Thus, in this paper, the influence of mooring line configuration and line diameter on surge motion and restoring behaviour is accessed using an in-house Mooring line quasi-static analysis code named as MLQSC.

2. Mooring Line And Quasi Static Analysis

Mooring lines provide resistance to environmental loading by deforming and activating reaction forces. Depending on the mechanism from which the tension effect of the mooring line is derive (hanging catenary effect or line elastic effect), they are classified as Catenary and Taut mooring lines respectively[16, 17].

Explicit presentation of mooring line analysis is available in [6, 18, 19]. Niedzwiecki and Casarella [20] presented one of the earliest contributions in the form of a computational algorithm for solving dimensionless catenary equations of the mooring line. A variant approach for the determination of tension-displacement of a slack mooring line was also presented in [21]. Similarly, a case of a single-point mooring system with uniform cable was studied by Nath and Felix[22] to predict mooring line motion and tensions resulting from oscillating wave forces.

In Quasi Static analysis, when the floating platform moves under the influence of wind, water waves and current, the mooring line geometry tend to change with respect to the magnitude of the forces causing the Platform motion. Tension of mooring line at each fairlead location is depict the motion of the floating platform. Computation of this relationship (Force-Excursion) is implemented using the catenary formulations.

Force - excursion (fairlead-anchor distance) relationship of a mooring system is established using mooring line material properties, initial pretension, and water depth. The force-excursion relationship provides the basis for computation of mooring line restoring forces. The initial excursion is calculated using initial pretension and based on the initial mooring line excursion and maximum platform offset, varying mooring line excursions are iteratively calculated. Furthermore, Top tension- Excursion relationship is formulated with reference to the mooring line breaking load to allow for maximum platform excursion.

The common practice is to analyse the behaviour (restoring) of a single mooring line, based on platform horizontal offset, updated excursion of each mooring line is calculated using individual azimuth angle distribution. Combine restoring influences of mooring line is presented in the form of a Force-Excursion Curve.

For a multicomponent mooring line, horizontal (X_m) and vertical projections (Y_m) of any segment hanging freely under its weight (kN/m) is obtained using the catenary formulations in reference [23].

$$X_m = \frac{H_t}{W}([Sinh^{-1}(tan\theta_t)] - [Sinh^{-1}(tan\theta_b)]) \quad (1)$$

$$Y_m = \frac{H_t}{W} Cosh([Sinh^{-1}(tan\theta_t)] - Cosh[Sinh^{-1}(tan\theta_b)]) \quad (2)$$

$$tan\theta_b = \frac{(V_t - ws)}{H_t} \quad (3)$$

Where $V_t = H_t tan\theta_t$ (4)

Resulting extension of each line segment due to increased tension line is approximately calculated using (5).

$$S_i = S_{i-1}\left(1 + \frac{T_i - T_{i-1}}{EA}\right) \quad (5)$$

Where, i is the configuration number, T_i is the average segment tension and EA is the segment modulus of elasticity.

Furthermore, resultant horizontal force H, for an excursion δ will be computed using (6)

$$H(\delta) = \sum_{j=1,p} H_j(\delta_j) Cos(\pi - \theta_j) \quad (6)$$

Where, $H_j(\delta_j)$ is the associated horizontal force and $\delta_j = \delta Cos(\pi - \theta_j)$ excursion of each mooring line.

3. Mooring Line Arrangement And Diameters Considered In This Study

Four different mooring configurations in four different wave heading were considered as illustrated in Table 2. Nomenclature of the mooring configuration is in the form; 4x3. Where 4 stands for the number of groupings while 3 represents the number of mooring lines per group.

Each of the mooring line groupings is analysed with one mooring line aligned in the wave heading as illustrated in Fig. 2 with the angle between groups maintained at 90 degrees. The azimuth angle of one mooring line is aligned to the wave heading while for other lines in the same group varies by -5º, +5º and 10º respectively.

Depending on the size of the floating platform, a variety of diameter is available depending on the mooring material[24]. Diameters 108mm,114.3mm,120.7mm and 133.4mm steel wire mooring line were investigated.

Table 1: Mooring Configuration considered in this study

Group	**Configuration (degree)**				
Wave Heading	**30**	**35**	**40**	**45**	**Remarks**
4x3					
I	25,**30**,35	30,**35**,40	35,**40**,45	40,**45**,50	bold number indicate the reference line to the wave heading
II	115,**120**,125	120,**125**,130	125,**130**,135	130,**135**,140	
III	205,**210**,215	210,**215**,220	215,**220**,225	220,**225**,230	
IV	295,**300**,305	300,**305**,310	305,**310**,315	310,**315**,320	
Evenly Spread					
I	0,**30**,60, 90,**120**,150, 180,**210**,240, 270,**300**,330	5,**35**,65, 95,**125**,155, 185,**215**,245, 275,**305**,335	10,**40**,70, 100,**130**,160, 190,**220**,250, 280,**310**,340	15,**45**,75, 105,**135**,165, 195,**225**,255, 285,**315**,345	
3X4					
I	25,**30**,35,40	30,**35**,40,45	35,**40**,45,50	40,**45**,50,55	
II	145,**150**,155,160	150,**155**,160,165	155,**160**,165,170	155,**165**,170,175	
III	265,**270**,275,280	270,**275**,280,285	275,**280**,285,290	280,**285**,290,295	
6X2					
I	**30**,25	**35**,20	**40**,35	**45**,40	
II	**75**,70	**80**,75	**85**,80	**90**,85	
III	**120,**115	**125**,120	**130**,125	**135**,130	
IV	**210**,205	**215**,210	**220**,215	**225**,220	
V	**255**,250	**260**,255	**265**,260	**270**,265	
VI	**300**,295	**305**,300	**310**,305	**315**,310	

4. Validation Of Numerical Code

The procedure itemise earlier was implemented using a MATLAB code **MLQSC** developed to compute the mooring line restoring forces of a Turret Moored FPSO. The code was validated using published experimental data [25] by making a comparison between the force-excursion curve of a Turret-moored FPSO from Offshore Technology Research Centre (OTRC) and that from the numerical code. The prototype mooring system consists of 12 mooring lines each of the type chain-polyester-chain, in 4 groups consisting of 3 mooring line (4x3) each, with an operating water depth of 1829m. But in the OTRC Experiment, 4 mooring lines were used with 1 equivalent mooring line representing each group. The test was conducted on 1:60 model. Mooring configuration of the OTRC FPSO is as shown in Fig 1.

Each of the middle mooring lines (in each group) are symmetrically distributed at 90 degrees from each other as in Fig. 1b.

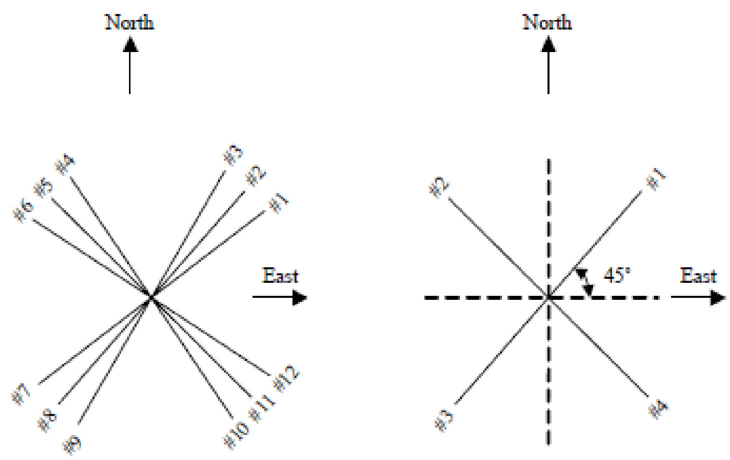

Fig. 1: (a) OTRC prototype mooring arrangement (b) OTRC Experiment mooring arrangement

Table 1 provides the OTRC prototype catenary mooring system properties.

Table 2: Main Particulars of OTRC FPSO Mooring System[25]

Segment of Mooring	Upper	Middle	Component
Material Type	Chain	Polyester	Chain
Length(m)	91.4	2438	121.9
Diameter(mm)	95.3	160	95.2
Submerged Weight(N/m)	1615	44.1	1615
Stiffness EA (kN)	820900	168120	820900
Breaking Load(kN)	7553	7429	7553
Pretension(kN)			1424
Water depth(m)			1829

5. Results and Discussion

5.1. Numerical Validation of MLQSC

The developed MATLAB code, MLQSC was validated by comparing restoring force numerically computed with the experimental results in [25]. Fig. 3 show a comparison between numerical and experimental result.

From Fig 3, excursion beyond 25m can be neglected since in practice the structure cannot be allowed more than 20m excursion.

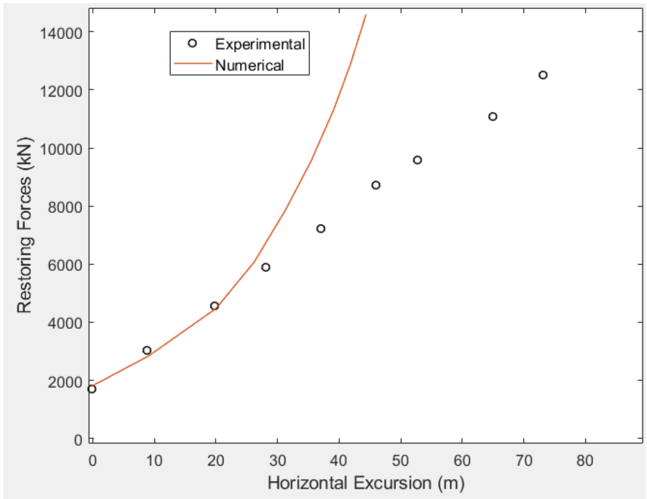

Figure 2: Comparison of numerical and Experimental restoring force for validation

5.2. Influence of Line Configurations on FPSO Restoring Forces

Variation of restoring forces for mooring configurations in different wave heading are illustrated in Fig 3,4 and 5. The influence of mooring number per group, as well as spread of the groupings to restoring behaviour of a turret moored FPSO mooring system, have been discussed. This is important considering the mode of operation of the turret mooring system which allows the FPSO to weathervane at 360^{o}.

Figure 3 show comparison of restoring behaviour of four mooring configurations in 30-degree wave heading. The evenly spread configuration can be observed to have higher restoring performance while the 6x2 configuration has the lowest performance. On the other hand, 3x4 and 4x3 have similar restoring behaviour (8629kN, 8485kN), respectively. All restoring variations for all mooring configurations are within same excursion limits.

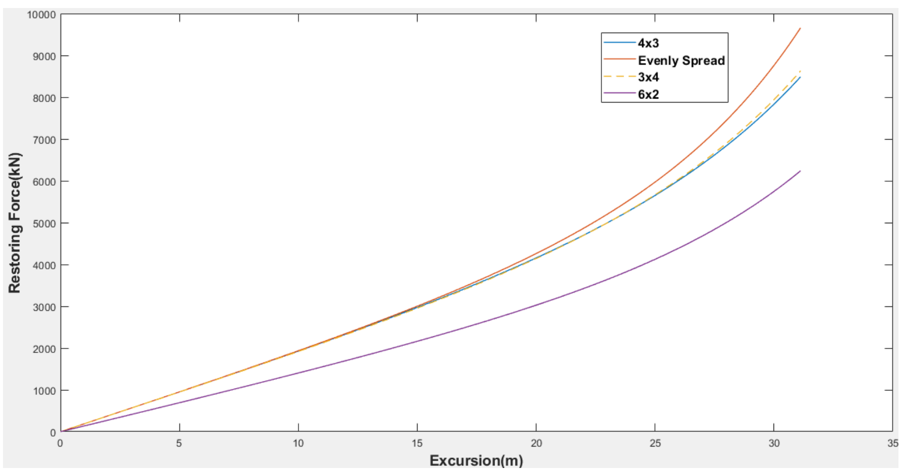

Figure 3: Comparison of Restoring Forces for different Mooring configuration at 30-degree wave heading

Figure 4 compare restoring behaviours at 35-degree wave heading. Unlike in Fig 3, variation in restoring behaviour between restoring behaviour of 3x4 and 4x3 configurations increases (8629kN,7928kN) with increasing azimuth variation with respect to the wave heading.

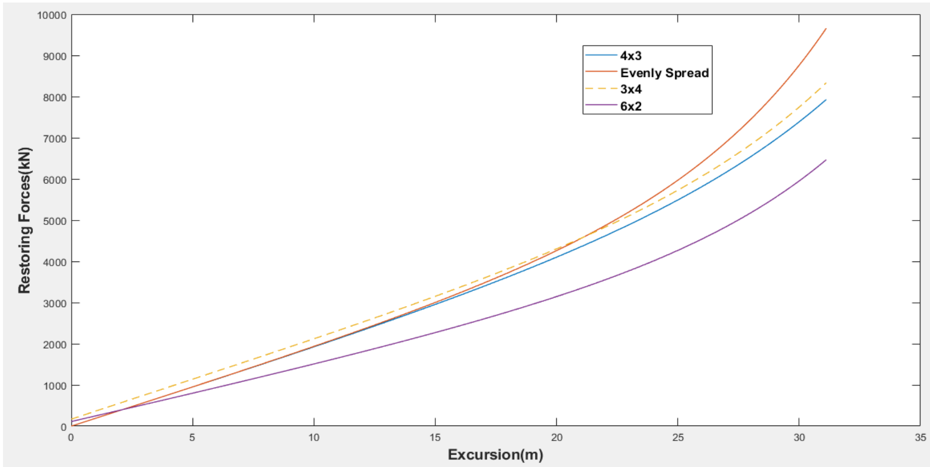

Figure 4: Comparison of Restoring Forces for different Mooring configuration at 35-degree wave heading

In Fig 5, the restoring performance comparison show similar trend except with increase in variation between 3x4 and 4x3 increase but this time with 4x3 having higher restoring performance than 3x4.

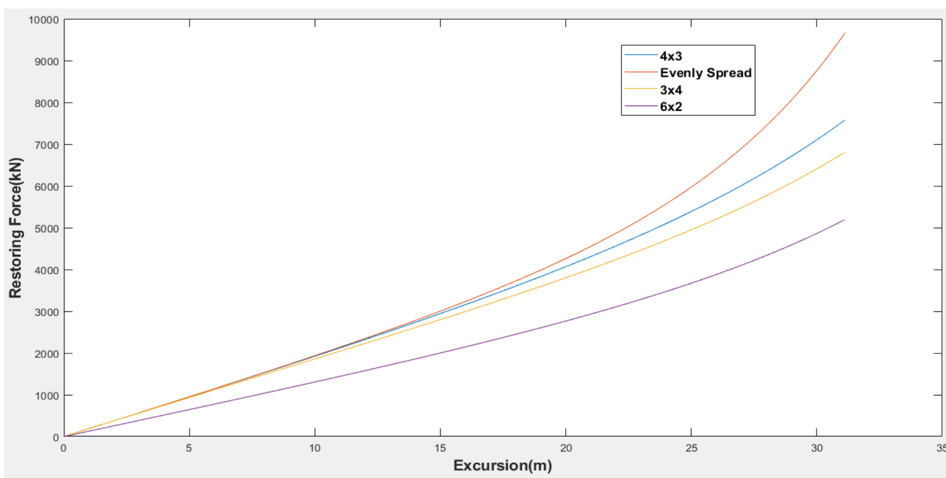

Figure 5: Comparison of Restoring Forces for different Mooring configuration at 40-degree wave heading

Fig 6 provides restoring performance comparison of different mooring configuration. Variation in the restoring performance of 4x3 and 3x4 tends to increase with an increase in the wave heading.

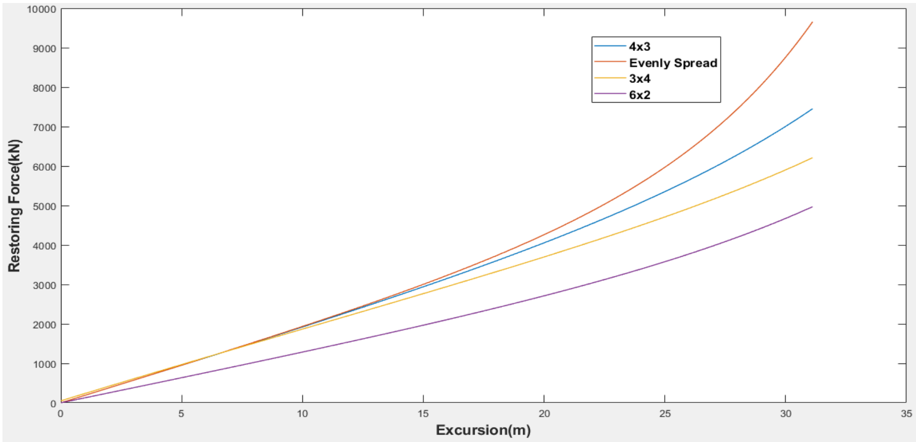

Figure 6: Comparison of Restoring Forces for different Mooring configuration at 45-degree wave heading

5.3. Influence of Line Diameter of FPSO Restoring Forces

Restoring behaviour of varying steel wire mooring line diameters in 3x4 configuration is shown in Fig 7. A general increase in restoring performance can be observed with an increase in line diameter. This behaviour might be attributed to the increase in submerged weight as the mooring diameter increase followed by a consequent reduction in the effective line tension and by implication decreasing the restoring forces. Also, from the same Fig 7, maximum horizontal excursions are observed to increase with an increase in mooring line diameter. This agrees well with the corresponding reduction in restoring behaviour.

In general, the effect of reduction in mooring line diameter on the restoring performance of the mooring system can be observed to be overwhelming as the diameter increase. Maximum variation in the excursion and restoring force for D108mm and D133.4mm can be observed to be 81% and 33.65% respectively.

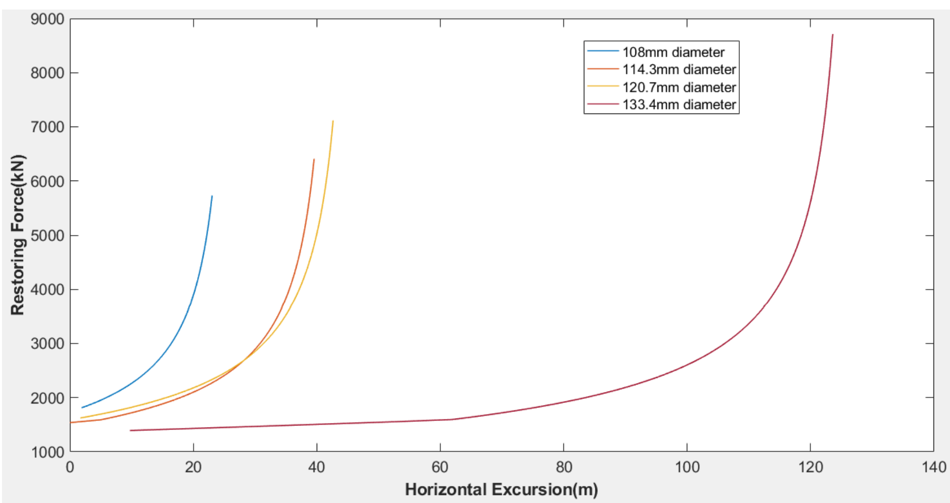

Figure 7: Influence of mooring line diameter on restoring force

6. Conclusion

Restoring behaviour of four (4) mooring configurations of a Turret moored FPSO in different wave heading was numerically analyse using an in-house Mooring Line Quasi-Static Analysis Code developed in MATLAB, named MLQSC. Influence of mooring line diameter on the restoring behaviour was also analysed.

The primary finding of this study is that the number of mooring lines per grouping has a significant role in dictating the restoring behaviour of a Turret Moored FPSO mooring system. However, this assertion was not consistent in the case of 3x4 and 4x3 configurations. Because 3x4 configuration (with 4 lines per group) exhibit better restoring performance at lower wave headings (30^o and 35^o), while the 4x3 configuration (with 3 lines per group) exhibit higher restoring forces at wave heading of 40^o and 45^o.

The specific conclusion drawn from this study are as follows:

1- The number of mooring configurations does not significantly result in the reduction of maximum horizontal excursions.
2- For different mooring configuration, restoring performance increases with an increase in wave heading.
3- Increase in mooring line diameter significantly result in a decrease in restoring performance (due to reduction in line tension) and consequent increase in corresponding Horizontal excursion

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