Research Journal of Applied Sciences, Engineering and Technology 8(3): 346-353, 2014
DOI:10.19026/rjaset.8.979
ISSN: 2040-7459; e-ISSN: 2040-7467

Submitted: February 14, 2014 Accepted: April 09, 2014 Published: July 15, 2014

Research Article

Effect of Mooring Line Properties and Fairlead Slopes on the Restoring Behavior of Offshore Mooring System

O.A. Montasir, A. Yenduri and V.J. Kurian
Department of Civil Engineering, Universiti Teknologi PETRONAS, Tronoh, Perak, Malaysia

Abstract: Mooring lines are used as station keeping systems for the deep-water floating offshore platforms. Mooring lines have considerable effect on the project overall cost. Therefore, it is necessary to economize their cost by choosing appropriate material and configuration which, in turn give the required responses for the platform by possessing good restoring capability. Hence, a numerical study has been conducted on the restoring behavior of the mooring system for different mooring line materials, line diameters and fairlead slopes. Two mooring systems consisting of mooring lines arranged unsymmetrical were considered. Assuming the drag forces on the mooring lines to be negligible and the change in the line geometry as insignificant, the mooring system has been analyzed using the quasi-static analysis. The numerical model thus developed has been validated using experimental model test data and a parametric study was conducted using the parameters mentioned. It can be concluded that the polyester mooring lines provide better restoring forces compared to the other materials and also the behavior of mooring system can be greatly affected with change in line diameter and fairlead slope.

Keywords: Fairlead slope, mooring line properties, mooring system, quasi-static analysis

INTRODUCTION

With increase in the demand for offshore production worldwide, the development in mooring technology is also increasing. As the platform water depths increase, there is a need for strong and lightweight mooring ropes. Hence, the mechanical properties of mooring ropes which drive the behavior of deep-water mooring systems are continuously improved to achieve a better design that balances strength of the lines with change in material, length and diameter.

From the last decade, there has been an increasing focus on the need for more cost-effective mooring systems for the floating platforms at greater water depths. Most of the studies were focused on the fibre rope properties. In early 1980s, it was learnt that yarn finished nylon ropes have good fatigue characteristics (Flory, 1982; Flory *et al*., 1987; Markussen *et al*., 1984). Later, polyester ropes were recommended as they are found to have better cyclic fatigue life because of its moderate stiffness and good compliance characteristics (Flory *et al*., 1985). Now-a-days polyester ropes are more commonly used for deep-water mooring lines; however, the high stretch of the polyester rope is a problem as the longer mooring lines allow greater horizontal offsets which may exceed the limits of the risers. Polyethylene ropes are also widely considered to be suitable for deep-water mooring lines due to their high strength and modulus (Flory *et al*., 2007a; Vlasblom *et al*., 2012).

The mooring system designers are still trying to understand the unique stretch and stiffness characteristics of these ropes to incorporate them into the design procedures. These characteristics are time dependent and linear/nonlinear. The fibre ropes usually experience elastic and permanent stretch when subjected to high tension (Flory *et al*., 2004). The fibre ropes are light weight, have minimum tension requirements and better corrosion resistance, involve simpler installation techniques and also help in reduction of the mooring footprint (Lee and Grove, 1999). Hence, the synthetic mooring lines have become a very attractive alternative to conventional steel catenary systems (Nielsen and Bindingbo, 2000).

Fibre rope technology defines the future of the moorings. Though the performance of the mooring system can be enhanced with increasing size/diameter of the mooring lines, over-sizing the ropes will reduce the fatigue design margins (Flory *et al*., 2007b). Similarly, the reduction in the fairlead slopes of the mooring lines enhances the performance of the system but this shall be accounted for the line lengths to be adopted in the design.

Design of mooring lines has been based on simple considerations of the dynamics combined with high safety factors. Recently, more advanced methods, including finite element methods have been employed

Corresponding Author: V.J. Kurian, Department of Civil Engineering, Universiti Teknologi PETRONAS, Bandar Seri Iskandar, 31750 Tronoh, Perak, Malaysia

to compute the mooring line loads. However, such methods are usually limited to the verification phase of a platform development project. The design phase still relies on simplified methods and quasi-static method is considered a better choice in the first approach as it is almost certain to achieve convergence (Nielsen and Bindingbo, 2000; Pascoal *et al*., 2005, 2006).

The study in this study includes developing a numerical code for the analysis of multi-component catenary mooring lines using quasi-static approach, which after validation with the experimental results, is used to conduct the parametric study. The motivation of the work lies in aiding the designers to economize the cost by choosing appropriate material and configuration that can give the desired responses for the platform. Hence, a numerical study has been conducted on the restoring behavior of the mooring system for different mooring line materials, diameter and fairlead slopes.

METHODOLOGY

Governing equations for the mooring line analysis: The nonlinear relationship between the restoring force and horizontal excursion of a mooring line usually requires an iterative solution. The key assumptions made for the analysis of mooring lines are:

- Components of the mooring line move very slowly so that the drag forces on the line can be treated as negligible
- Change in the line geometry is insignificant and thereby the in-line force due to direct fluid loading caused from the waves is also insignificant
- The clump weight segment is inextensible
- Only horizontal excursion of the line is considered

Using the equation of a catenary for the evaluation of force-excursion relationship of the mooring line, the vertical and horizontal projection of any segment hanging freely under its own weight w per unit length is as given in Eq. (1) and (2):

$$Y = \frac{H_t}{w}[\cosh\{\sinh^{-1}(\tan(\theta_t))\} - \cosh\{\sinh^{-1}(\tan(\theta_b))\}] \quad (1)$$

$$X = \frac{H_t}{w}[\sinh^{-1}(\tan(\theta_t)) - \sinh^{-1}(\tan(\theta_b))] \quad (2)$$

The extension of any segment under increased line tension can be evaluated using Eq. (3):

$$S = S_0\left(1 + \frac{T - T_0}{EA}\right) \quad (3)$$

where,
T_0 : Initial line tension when the segment length is S_0
T : Increased average line tension

The analysis has been carried out for the mooring line with disturbed clump weight by referring to the procedure steps mentioned in Agarwal and Jain (2003), incorporating the two conditions stated for the lifting-off of the clump weight. The behavior of the mooring system i.e., the resultant horizontal force H, for an excursion δ can be computed using the Eq. (4):

Table 1: MARLIN truss spar mooring configuration (azimuth angles are mentioned with respect to wave heading south)

Group	Configuration
I	0°, 5°, 5°
II	115°, 120°, 125°
III	235°, 240°, 245°

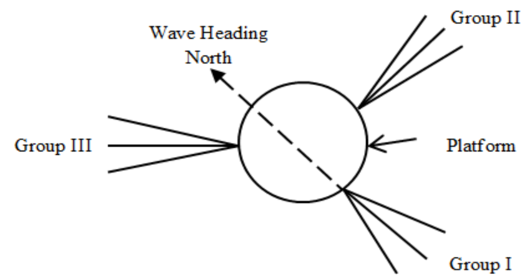

Fig. 1: Mooring arrangement of the platform used for validation

$$H(\delta) = \sum_{j=1,p} H_j(\delta_j)\cos(\pi - \theta_j) \quad (4)$$

where,
p : Total number of mooring lines
θ_j : Angle between the j^{th} mooring line and the direction of excursion
δ_j : Excursion for the j^{th} mooring line
$H_j(\delta_j)$: Associated horizontal force with $\delta_j = \delta\cos(\pi - \theta_j)$

Numerical modelling of the mooring lines: Mooring lines restoring behavior helps to keep the motions of a floating platform within the desired range. Performance of the mooring system can be greatly affected with line material, diameter, fairlead slopes. Hence, investigating the behavior of mooring lines for above parameters aids in deciding the best suitable, both in terms of performance of the moorings as well as economizing the project overall cost.

To compute the restoring forces of mooring lines, a MATLAB code named QSAML has been developed using quasi-static analysis. The numerical code is validated with experiment tests by comparing the mooring stiffness curve obtained for the MARLIN truss spar mooring configuration given in Table 1 and Fig. 1 (Downie *et al*., 2000; Flory *et al*., 1988; Gobat and Grosenbaugh, 2001; Mavrakos *et al*., 1996; Rosales and Filipich, 2006; Smith and MacFarlane, 2001).

Mooring lines typically consist of top, middle and lower components. The material properties-wet weight, effective modulus, breaking loads and lengths of the various components of the mooring line are as given in Table 2.

For this study, a floating platform having the fairleads at a height of 942 m from the sea bed is

Table 2: Characteristics of the MARLIN truss spar mooring lines

Legend	Top component	Middle component	Lower component
Type	Chain cable	Spiral strand cable	Chain cable
Length (m)	76.20	1828.700	45.70
Wet weight (kN/m)	2.73	0.636	2.73
Effective modulus (kN)	665852	1338848	858882
Breaking load (kN)	13188	12454	13188

Table 3: Mooring line configurations for the study (azimuth angles are mentioned with respect to wave heading south)

Group	Configuration-1 (one mooring line group in wave heading)	Configuration-2 (no mooring line group in wave heading)
I	0°, 5°, 5°	45°, 50°
II	115°, 120°, 125°	125°, 132.5°
III	235°, 240°, 245°	222.3°, 229.7°, 235°
IV	-	308.5°, 314.1°, 320.3°

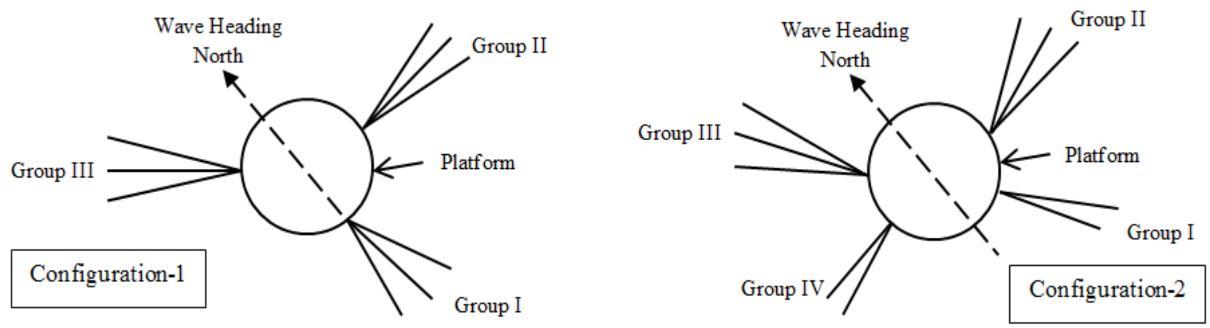

Fig. 2: Mooring lines arrangement of the platform in configuration: 1 and 2

Table 4: Characteristics of the mooring lines for different materials

Material	Wet weight (kN/m)	Effective modulus (kN)	Breaking load (kN)
Steel wire	0.60	1829534	7987
Nylon	0.39	36591	6574
Polyester	0.11	32021	13262
Polypropylene	0.31	18295	6142

Table 5: Characteristics of the mooring lines for different diameters

Diameter (mm)	Wet weight (kN/m)	Effective modulus (kN)	Breaking load (kN)
76.2	0.2986	911598	4005
82.6	0.3506	1069863	4693
88.0	0.3986	1215793	5326
95.3	0.4673	1424376	6231
101.6	0.5319	1620625	7082
108.0	0.6007	1829535	7987
114.3	0.6737	2051106	8947
120.7	0.7508	2285338	9960
127.0	0.8322	2532232	11029
133.4	0.9177	2791786	12152
139.7	1.0074	3064002	13329
146.1	1.1013	3348880	14560
152.4	1.1994	3646418	15846
165.1	1.4081	4279480	18581
177.8	1.6335	4963186	21534

Table 6: Characteristics of the mooring lines for different fairlead slopes

Fairlead slope (deg)	Length of the middle component of mooring line (m)
45.8	2250
50.0	1500
56.6	1200
59.4	1100
64.1	1000

considered. Two mooring line configurations as given in Table 3 and Fig. 2 are chosen for the study. (Note: Change in the characteristics of top and lower components is neglected as their effect on the restoring behaviour of mooring system is negligible).

Details of the study on mooring line materials, diameters and failead slopes are as follows.

Line materials: Restoring behaviour of the two mooring configurations is investigated for four commonly used line materials-steel wire, nylon, polyester and polypropylene.

Line diameters: The diamters of mooring lines for any floating platform usually range from 4” to 5” and slightly greater for very few cases. Here, steel wire mooring lines with diameters ranging from 3” to 7” (i.e., 76.2 to 177.8 mm) are studied.

Fairlead slopes: Study is conducted for steel wire moorings and varying the top slopes of lines from 45° to 65°. The change in mooring line length for different slopes is incorporated only in middle component keeping the lengths of top and lower component unchanged.

The characteristics of mooring lines used for this study are given in Table 4 to 6 with others as in Table 2.

RESULTS AND DISCUSSION

The results obtained from numerical code, QSAML and experiments tests conducted for mooring

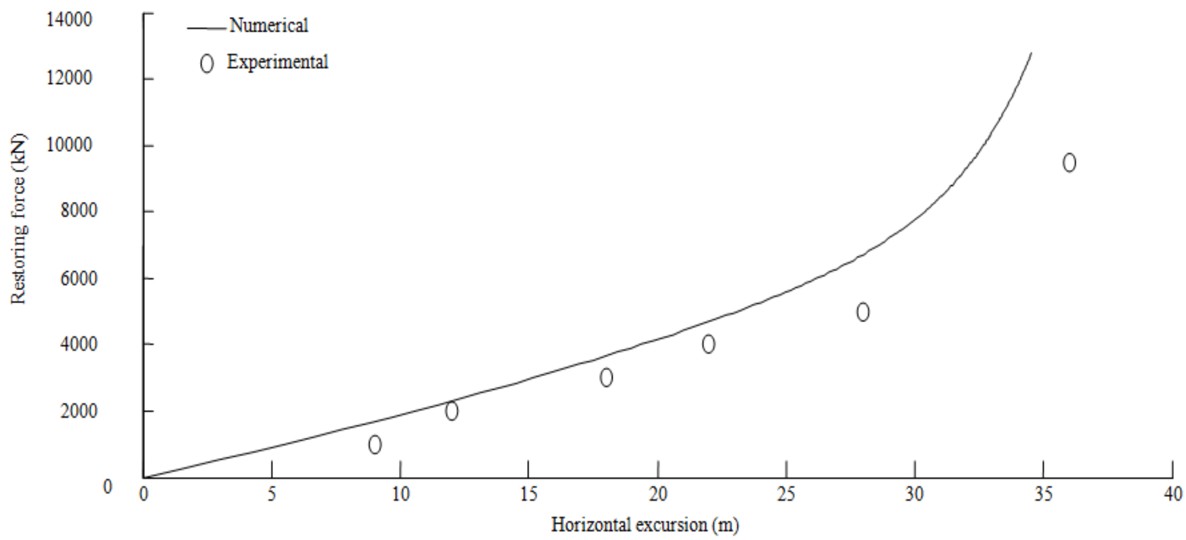

Fig. 3: Validation of numerical predictions with experimental measurements

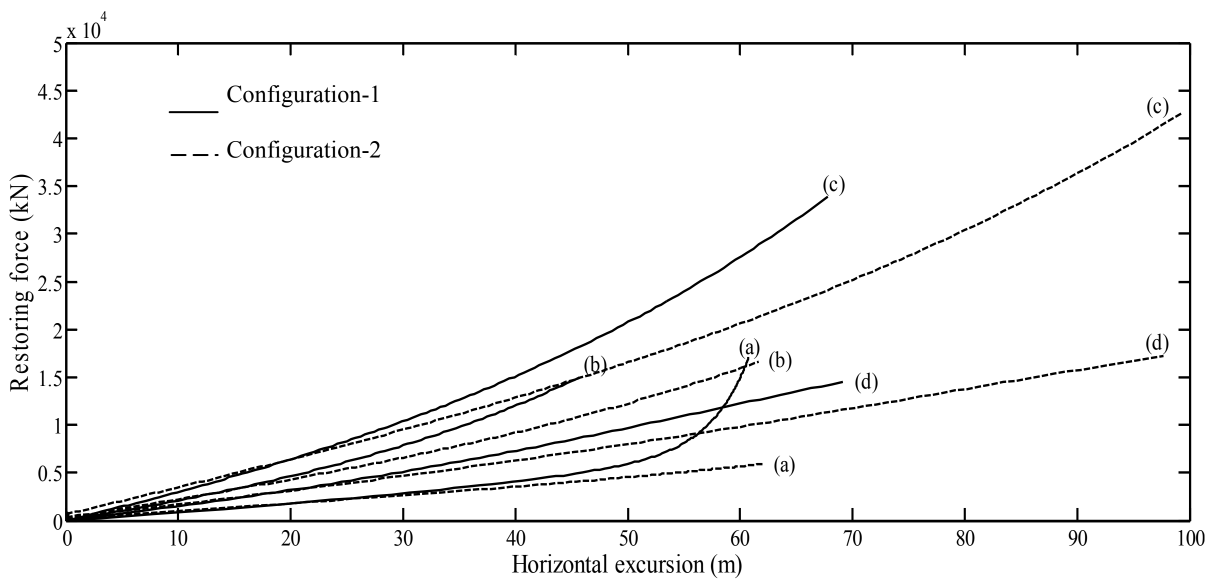

Fig. 4: Restoring behavior of mooring system with configuration: 1, 2 for different line materials

configuration given in Table 1, are as shown in Fig. 3. The experimental tests were performed on a 1:61 scale truss spar model by Amooc in Offshore Technology Research Centre (OTRC) wave tank at Texas A&M University (Ran, 2000).

The difference in the results can be attributed to change in the mooring line set up between the prototype and experimental model i.e., the prototype is considered with nine mooring lines whereas experimental model with only five mooring lines (one line from group: I, III and three lines from group-II); which otherwise can be concluded that there is a good agreement between the numerical and experimental results.

The discussions on restoring behavior of two mooring line configurations for parameters (line material, diameter and fairlead slopes) studied are as follows.

Line materials: Figure 4 shows the restoring behavior of mooring system with configurations: 1 and 2 for (a) steel wire; (b) nylon; (c) polyester and (d) polypropylene mooring line materials. It can be inferred that restoring performance by the polyester mooring lines for both configurations is relatively higher compared to other materials. The restoring performance of other mooring line materials for both configurations is-(in order) nylon, polypropylene and steel wire lines.

It can also be observed that in general, the configuration having mooring line group in wave heading gives better restoring behavior when

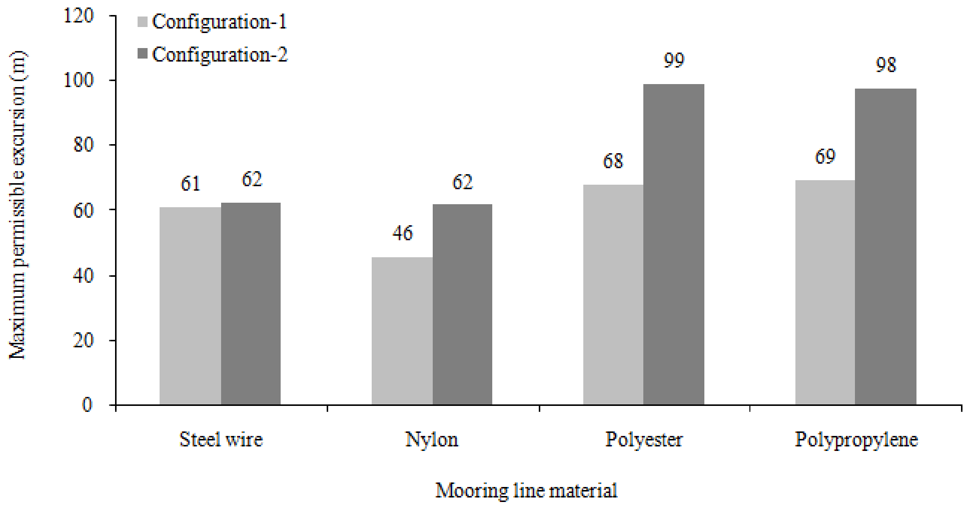

Fig. 5: Maximum permissible horizontal excursion of mooring configurations: 1, 2 for different line materials

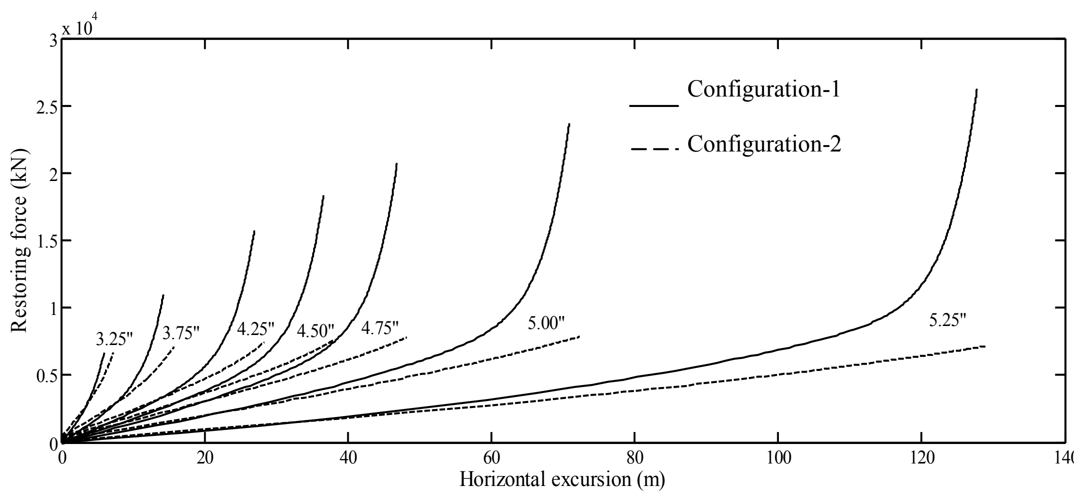

Fig. 6: Restoring behavior of mooring system with configuration: 1, 2 for different line diameters

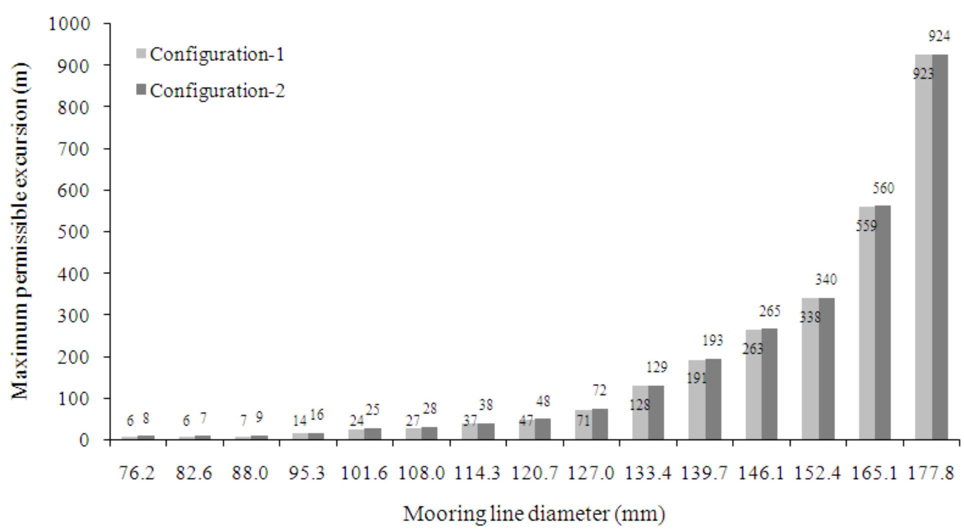

Fig. 7: Maximum permissible horizontal excursion of mooring configurations: 1, 2 for different line diameters

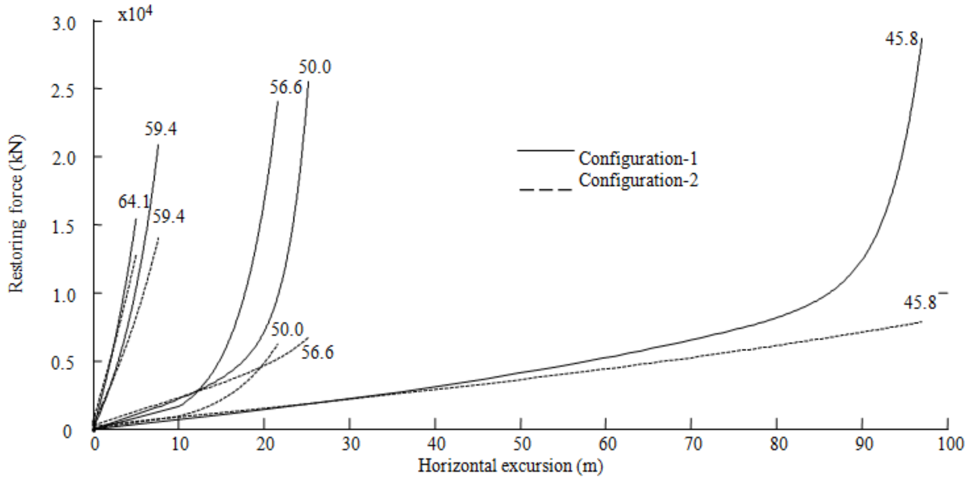

Fig. 8: Restoring behavior of mooring system with configuration: 1, 2 for different fairlead slopes

compared to the configuration not having any mooring line group in wave heading. But it can be noticed that the difference in the restoring behaviors of two mooring configurations is insignificant up to relatively small horizontal excursions and vice-versa.

From Fig. 5, it can be observed that for both configurations: 1 and 2, the polyester and polypropylene mooring lines permit nearly same maximum horizontal excursions and also are the highest of all other materials.

For all the materials, maximum permissible horizontal excursions are more for configuration-2 than configuration-1. Among the four mooring line materials, highest difference between the maximum excursions attained by both configurations is exhibited by polyester and polypropylene, followed by nylon and steel wire i.e., polyester and polypropylene show a difference of 30 m (approx.), nylon 16 m but steel wire mooring lines show a difference of 1 m which can be considered as insignificant.

Line diameters: Figure 6 shows the restoring behavior of mooring system with configurations: 1 and 2 for line diameters ranging from 3" to 5.25" (Note: Behaviors for other line diameters are not shown in the figures to avoid congestion between the curves). It can be inferred that in general, the restoring behavior of mooring systems for both configurations decreases as the diameter of line is increased. This can be attributed to increase in the wet weight of mooring line with diameter which is causing the reduction in line tensions and leading to decrease in the restoring forces. It can also be observed that the difference in restoring behavior for both mooring configurations is found to increase with line diameters.

Similar to the study on line materials, it can be observed that in general, the configuration having mooring line group in wave heading gives better restoring behavior when compared to the configuration not having any mooring line group in wave heading. But it can be noticed that the difference in the restoring behaviors of two mooring configurations is insignificant up to relatively small horizontal excursions and vice-versa.

Figure 7 shows variation of the maximum permissible horizontal excursions of mooring system in both configurations for different line diameters. It can be inferred that the mooring lines of large diameters permit relatively high horizontal excursions.

For all the mooring line diameters, maximum permissible horizontal excursions attained by the configuration-2 are more than configuration-1. The difference between the maximum excursions attained by both configurations is comparatively less for all the mooring line diameters i.e., highest difference observed is 1.8 m which can be considered as insignificant.

Fairlead slopes: Figure 8 shows the restoring behavior of mooring system with configurations: 1 and 2 for fairlead slopes ranging from 45° to 65°. It can be inferred that the restoring behavior of mooring systems for both configurations increases as the fairlead slope/top slope increases.

Similar to the study on line materials and diameters, it can be observed that in general, the configuration having mooring line group in wave heading gives better restoring behavior when compared to the configuration not having any mooring line group in wave heading and also it can be noticed that the difference in the restoring behaviors of two mooring configurations is insignificant up to relatively small horizontal excursions and vice-versa.

From Fig. 9, it can be inferred that the maximum permissible horizontal excursion of mooring system for both configurations decreases as the fairlead slope increases. At fairlead slope of nearly 45^0, the mooring system for both configurations permits relatively large horizontal excursion compared to other fairlead slopes.

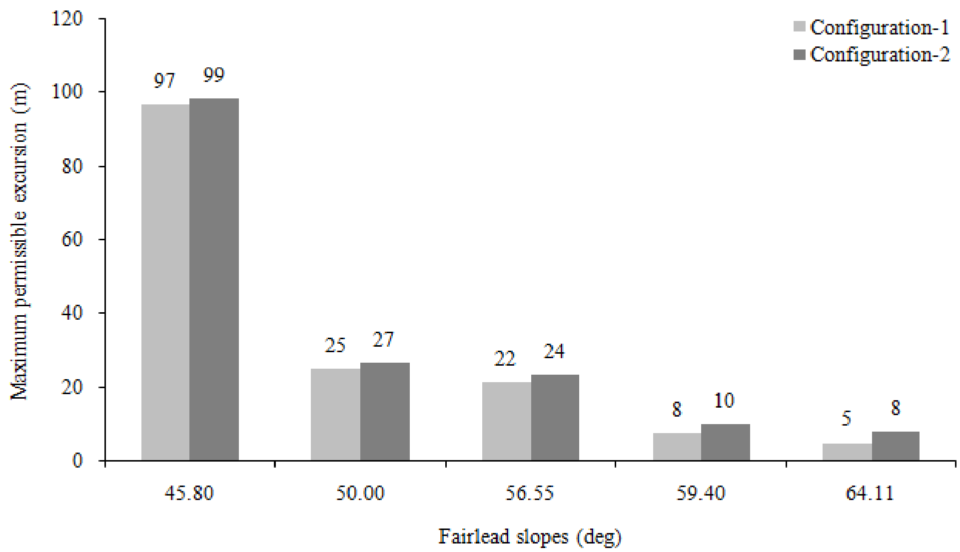

Fig. 9: Maximum permissible horizontal excursion of mooring configurations: 1, 2 for different fairlead slopes

In general, for all the fairlead slopes, maximum permissible horizontal excursions attained by the configuration-2 are more than configuration-1 but the difference in these maximum excursions between configurations: 1 and 2 can be considered as insignificant.

CONCLUSION

To conduct the study, a numerical code QSAML has been developed using quasi-static analysis and has been validated with experimental measurements. Based on the study conducted in this study on mooring line materials, diameters and fairlead slopes, following conclusions can be drawn on the behavior of mooring systems:

- Generally, configuration having mooring line group in the wave heading gives better restoring behavior than configuration not having any mooring line group in wave heading.
- Mooring configuration not having line group in wave heading permit more horizontal excursions than configuration having line group in wave heading.
- For any configuration, mooring systems with the polyester lines offer relatively higher restoring performance compared to other commonly used materials.
- Polyester and polypropylene mooring lines permit nearly same maximum horizontal excursions. The difference in maximum permissible horizontal excursions is significant for polyester, polypropylene, nylon and insignificant for steel wire mooring lines. The highest difference is exhibited by polyester and polypropylene lines.
- For any configuration, the restoring behavior of mooring systems decreases with increase in line diameter. Mooring lines with relatively large diameters allow high horizontal excursions and vice-versa.
- The restoring behavior of mooring systems with any configuration increases as fairlead slope of the mooring line is increased. Mooring lines with fairlead slope of 45° permit relatively large horizontal excursions compared to other fairlead slopes.

REFERENCES

Agarwal, A.K. and A.K. Jain, 2003. Dynamic behaviour of offshore spar platforms under regular sea waves. J. Ocean Eng., 30: 487-516.

Downie, M.J., J.M.R. Graham, C. Hall, A. Incecik and I. Nygaard, 2000. An experimental investigation of motion control devices for truss spars. J. Marine Struct., 13: 75-90.

Flory, J.F., 1982. New and used strength of large marine hawsers. Proceeding of the Offshore Technology Conference. Houston, Texas, Paper No: OTC 4304.

Flory, J.F., J.W.S. Hearle and M. Goksoy, 1987. Abrasion resistance of polymeric fibres in marine conditions. Proceeding of the 2nd International Conference on Polymers in a Marine Environment. IME, London.

Flory, J.F., M.R. Parsey and H.A. McKenna, 1988. The choice between nylon and polyester for large marine ropes. Proceeding of the 7th Conference on Offshore Mechanics and Arctic Engineering. ASME, New York.

Flory, J.F., S.P. Banfield and D.J. Petruska, 2004. Defining, measuring and calculating the properties of fiber rope deepwater mooring lines. Proceeding of the Offshore Technology Conference. Houston, Texas, Paper No: OTC 16151.

Flory, J.F., S.P. Banfield and C. Berryman, 2007a. Polyester mooring lines on platforms and MODUs in deep water. Proceeding of the Offshore Technology Conference. Houston, Texas, Paper No: OTC 18768.

Flory, J.F., Ahjem and S.P. Banfield, 2007b. A new method of testing for change-in-length properties of large fiber-rope deepwater mooring lines. Proceeding of the Offshore Technology Conference. Houston, Texas, Paper No: OTC 18770.

Gobat, J.I. and M.A. Grosenbaugh, 2001. A simple model for heave-induce dynamic tension in catenary moorings. J. Appl. Ocean Res., 23: 159-174.

Lee, M.Y. and T. Grove, 1999. Use of synthetic ropes in deepwater moorings: ABS guidance notes. Proceeding of the Riding the Crest into the 21st Century (OCEANS '99 MTS/IEEE). Seattle, WA, 1: 257-268.

Markussen, B.H., E.S. Hunt and R.E. Hobbs, 1984. Wear of nylon hawsers over rollers, pulleys and fairleads. Proceeding of the 16th Offshore Technology Conference. Houston, Texas, Paper No: OTC 4765.

Mavrakos, S.A., V.J. Papazoglou, M.S. Trintafyllou and J. Hatjigeorgiou, 1996. Deep water mooring dynamics. J. Marine Struct., 9: 181-209.

Nielsen, F.G. and A.U. Bindingbo, 2000. Extreme loads in taut mooring lines and mooring line induced damping: An asymptotic approach. Appl. Ocean Res., 22: 103-118.

Pascoal, R., S. Huang, N. Barltrop and C.G. Soares, 2005. Equivalent force mdel for the effect of mooring systems on the horizontal motions. Appl. Ocean Res., 27: 165-172.

Pascoal, R., S. Huang, N. Barltrop and C.G. Soares, 2006. Assessment of the effect of mooring systems on the horizontal motions with an equivalent force to model. J. Ocean Eng., 33: 1644-1668.

Ran, Z., 2000. Coupled dynamic analysis of floating structures in waves and currents. Ph.D. Thesis, Texas A&M University, Texas.

Rosales, B. and C.P. Filipich, 2006. Full modelling of the mooring non-linearity in a two-dimensional floating structure. Int. J. NonLin. Mech., 41: 1-17.

Smith, R.J. and C.J. MacFarlane, 2001. Statics of a three component mooring line. J. Ocean Eng., 28: 899-914.

Vlasblom, M.P., J. Boesten, S. Leite and P. Davies, 2012. Development of HMPE fiber for permanent deepwater offshore mooring. Proceeding of the Offshore Technology Conference. Houston, Texas, Paper No: OTC 23333.