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Mooring Line Reliability Analysis of Single Point Mooring (SPM) System under Extreme Wave and Current Conditions

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ABSTRACT

Single Point Mooring (SPM) is a type of offshore facility that is used for the loading and unloading of oil and gas tankers in the sea. In Iran, it is briefly called “floating buoy”. The present study discussed floating type, fixed to the seabed with mooring chain. The mooring chain of SPM, which is considered one of the important parameters of its design, will be evaluated with regard to reliability in different environmental conditions. Reliability is the likelihood of a healthy and flawless functionality for a specific time according to existing and predetermined conditions. OrcaFlex Ver. 9.4e (UK) software, by Orcina Company was used for moorings analysis. For this purpose and to calculate the environmental forces in the mooring chains (in our case 6 mooring chains with a 60 degree angle), the researchers used the diffraction analysis and time history. The results revealed that; by decreasing and increasing the diameter of the mooring chain, the force applied to the mooring also decreased and increased, respectively. Also, the effects of chain diameter, direction, and amount of wave and current were studied. The behavior of wave and current showed that when the direction of the wave and the current were closer to the direction of each mooring chain, the force applied to the mooring increased. To calculate the reliability, the FORM[1] method was employed, and to find the target point on the function, the MPP[2] method was used. The reliability of mooring was intended to control, the value of reliability index (β), using a software program written in MATLAB, for the environment loads with a return period of 100 years. The reliability index for mooring lines of SPM was greater than 3.51, representing the safe performance of the mooring lines under environmental load.

[1] First Order Reliability Method
[2] Most Probable Point
[3] Single Point Mooring

1. Introduction

Different stages of selection, design and construction of any marine structure involve accepting all kinds of risks and then exploiting the stage, expecting to function successfully and safely. The purpose of this study is to analyze the applied random and probabilistic viewpoint in designing and analyzing moorings of SPM. Due to the high cost of running a marine facility (including a SPM) and its highly sensitive operation, the reliability and risk assessment of its design and operation, and in particular its mooring line operation, are very important, and the results of this risk can be used to check reliability and risk. Among the components of a floating marine structure, its mooring system is of particular importance in maintaining the position of the floating structure in its place. Various parameters are also available for the design of the mooring systems, such as the type of containment, resistance of the mooring line, the seabed pattern, environmental conditions and duration of operation. Therefore, several aspects have to be considered in order to define the optimal mooring system, (i.e., a system that leads to the displacement of the minimum unit of float). In this paper, firstly, the environmental forces (wave & current) were introduced into the flotation control system based on the characteristics of the mooring line under these forces. Then, the probability of failure of each mooring line was studied using these forces [1].

In this paper, firstly, the type and characteristics of the mooring line of SPM is described and secondly the theory of reliability calculation is explained. Besides, the environmental and marine conditions of Bahregan oil terminal are presented as case study. Furthermore, the modeling of the mooring line of SPM and the results of their forces are presented. In the following, the results of this research are presented and finally, the values of the mooring line reliability are compared with the values set in the standard [4].

2. Static Analysis of Catenary Mooring Lines

Figure 1 shows an element of the containment lines located at a depth of z from the water surface. In this figure, F and D, respectively, represent the vertical and tangential hydrodynamic forces entering the length of the line of mooring; w is the weight of the unit length of the mooring line; A is the cross section of mooring line; E is the elasticity of the line of mooring, and T is the tensile strength along the mooring line. Using equilibrium equations, the static characteristics of the mooring lines were extracted. Figure 2 shows the characteristics [2].

Based on [3] and according to [4], the forces involved in a CALM[4] mooring system are calculated as follows:

The maximum horizontal force tolerated by the mooring system ($T_{H\,max}$) is calculated by equation (1):

$$T_{H\max} = AE\sqrt{\left(2\frac{T_{\max}}{wh}+1\right)^2 - \frac{2wh}{AE}} - AE \qquad (1)$$

In this equation, T_{max} is the maximum force of the mooring system; AE is the rigidity of the mooring system; w is the weight of the mooring system, and h is the depth of water.

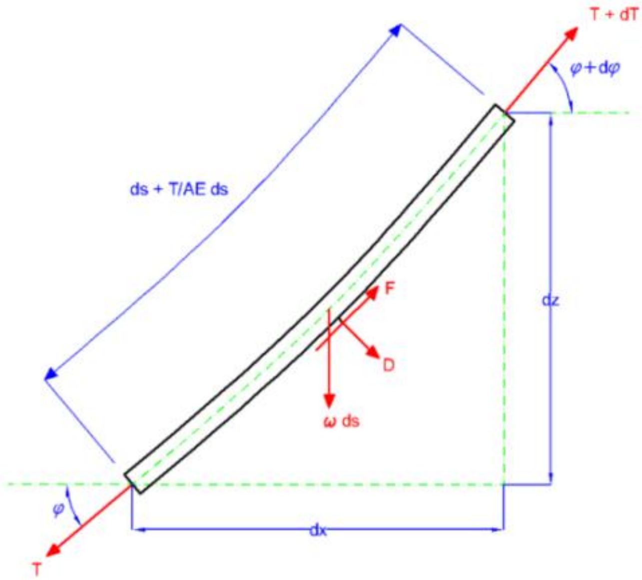

Figure 1. Forces on the Element of Mooring [5]

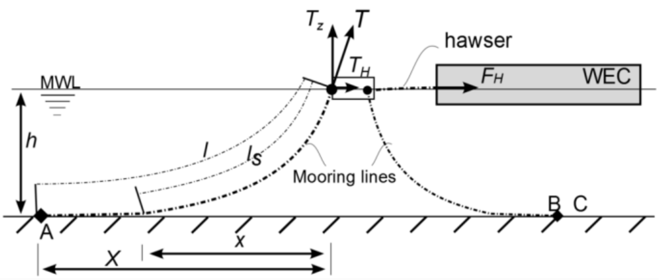

Figure 2. Mooring Line of SPM from CALM type [2]

3. Reliability Analysis

One of the reliability analysis methods is the first-order reliability method (FORM). In this paper, the reliability parameters were obtained based on the combination of the above method and the response surface method. It was also in accordance with a study conducted by Du Xiaoping in 2005 at the University of Missouri, America [6].

Probabilistic integrals for an issue with two variables are depicted in Figure 3.

[4] Catenary Anchor Leg Mooring

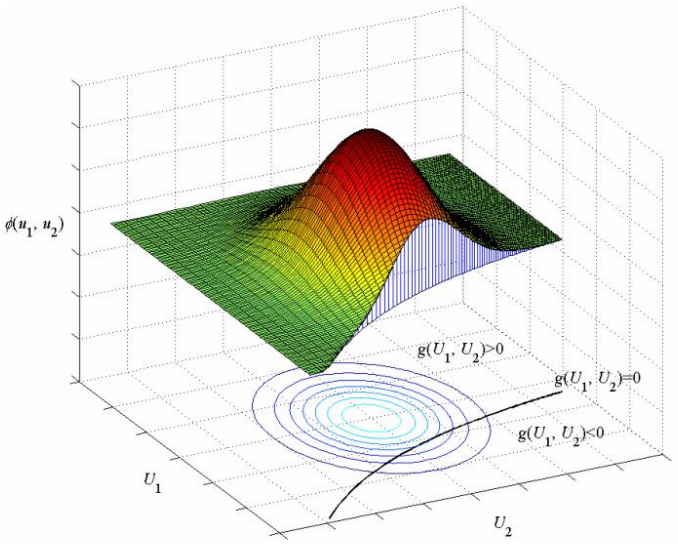

Figure 3. Probability Distribution Functions [6]

Step 1: Simplify the sub-integral function

For this purpose, first, the problem variables are transmitted from space X to space U.

The probability of failure (p_f) is expressed in equation (2):

$$p_f = \iint_{g(u_1,u_2,\dots u_n)<0} \prod_{i=1}^{n} \frac{1}{\sqrt{2\pi}} e^{\left(-\frac{1}{2}u_i^2\right)} du_1\, du_2 \dots du_n \qquad (2)$$

Step 2: Approximation of the integral boundary

To minimize the loss of accuracy in the linearization process, it is natural that the function g(U) extends around a point with the largest share in the probability integral. In other words, the function g(U) extends around a point where the sub-integral function at that point has a maximum value. This point, which lies on the boundary g(U)=0, is called MPP. The maximization of the common probability distribution function $\emptyset_u(u)$ under g(U)=0 defines the MPP location.

The problem of finding the MPP point is:

$$\begin{cases} min\|u\| \\ subject\ to\ g(u) = 0 \end{cases} \qquad (3)$$

Where $\|u\|$ is dimensioned and expressed as equation (4):

$$\|u\| = \sqrt{u_1^2 + u_2^2 + \cdots + u_n^2} = \sum_{i=1}^{n} u_i^2 \qquad (4)$$

Solving this problem ultimately leads to finding the MPP point, or $u^* = (u_1^*, u_2^*, \dots, u_n^*)$. MPP is the shortest dot distance on the function g(U)= 0 to source O in space U (Figure 4). The minimum distance $\beta = \|u^*\|$ is called the Reliability Index.

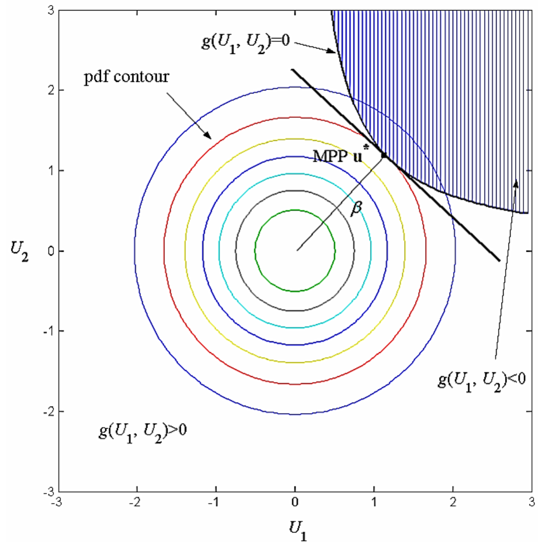

Figure 4. View of the Contour Function [6]

By slightly simplifying the reliability relation, equation (5) is obtained:

$$R = 1 - p_f = 1 - \emptyset(-\beta) = \emptyset(\beta) \qquad (5)$$

Equation Φ(β) is as follow:

$$\Phi(\beta) = \frac{1}{\sqrt{2\pi}} \int_{-\infty}^{\beta} e^{-\frac{x^2}{2}} dx \qquad (6)$$

The flowchart of finding MPP:

To find the point $u^* = (u_1^*, u_2^*, \dots, u_n^*)$, the flowchart shown in Figure 6 is used:

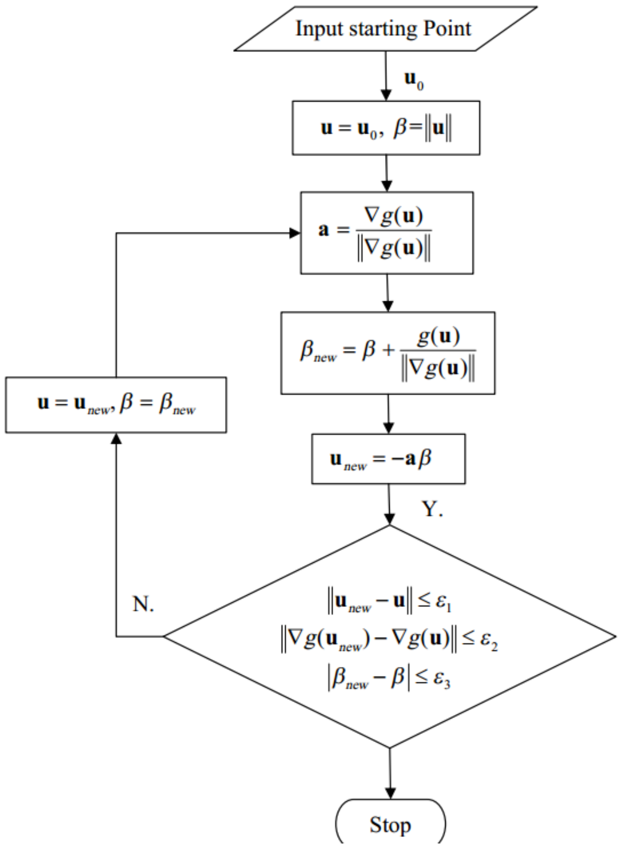

Figure 5. The Flowchart of Finding MPP [6]

Box-Behnken method [6]

In this method, the experimental stages, on a form of several orbits with the same distance, are located at a distance equal to the central point, (Figure 6) for a three-factor design. The main feature is that all levels of the factor must be set at three levels (-1, 0, +1), with equal interstices between these levels.

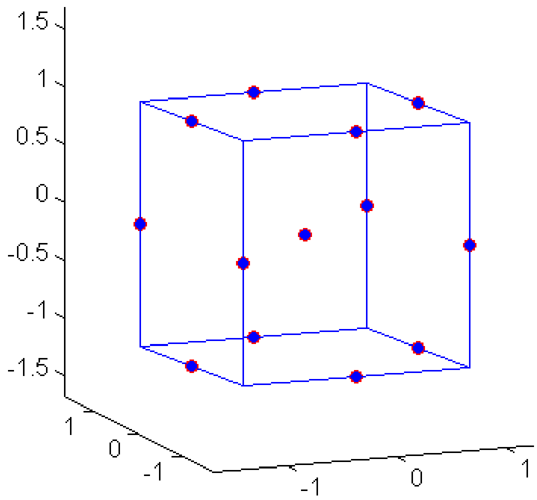

Figure 6. Discrete Points in the Box-Behnken Design Method [7]

Table 1. 13 Combinations of Independent Variables [6]

Experimental Order [*Run*]	Variable Factors		
	X(1)	X(2)	X(3)
1	-1	-1	0
2	-1	1	0
3	1	-1	0
4	1	1	0
5	-1	0	-1
6	-1	0	1
7	1	0	-1
8	1	0	1
9	0	-1	-1
10	0	-1	1
11	0	1	-1
12	0	1	1
13	0	0	0

The general formula for the response surface method is presented below:

$$Y = a_0 + \sum_{i=1}^{k} a_i X_i + \sum_{i=1}^{k} \sum_{j=1}^{k} a_{ij} X_i X_j + \sum_{i=1}^{k} a_{ii} X_i X_i \qquad (7)$$

Where a_i is the coefficient of the equation, and X_i and X_j are variables. Based on the Box-Behnken method, 13 combinations of independent variables should be considered.

4. Case Study

A case study was carried out on the environmental forces of the floating point project to export the Azadegan extra heavy crude oil by Tehran Berkeley Consulting Engineers in the Bahregan oil terminal [8]. The Bahargan oil terminal in the west of the Persian Gulf is located in Bushehr province, adjacent to Bandar Imam Hassan port. The statistical data used in the Bahragan project to determine the parameters of environmental forces based on ISWM[5] were obtained from the Ports and Maritime Organization for project studies. Mike21 software was also used to predict environmental forces for different return periods (Figures 7).

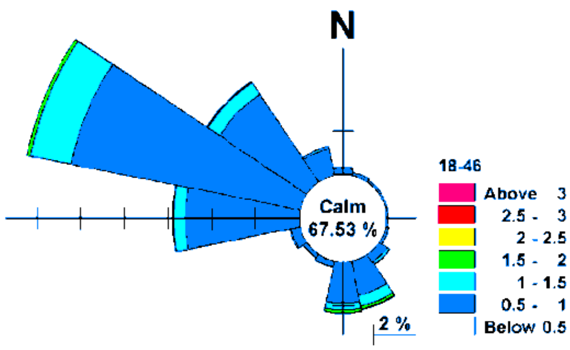

Figure 7. Wave Rose of the Bahrgan Zone Based on ISWM [8]

EVA[6] was used to predict the amount of waves in different periods. Based on EVA analysis performed using Mike 21 software, the amounts of environmental forces (wave and current) at the site with a return period of 100 years and in eight directions, 0, 45, 90, 135, 180, 225, 270 and 315 degrees are presented in the Table 2.

Table 2. Specifications of Environmental Forces with a 100-year Return Period [8]

No.	Direction [*degree*]	Wave Height [*m*]	Wave Period [*s*]	Current Velocity [*m/s*]
1	0	2.9	5.5	0.54
2	45	3.0	5.6	0.50
3	90	4.1	6.5	0.48
4	135	5.2	7.2	0.55
5	180	8.3	8.7	0.60
6	225	0.9	3.4	0.50
7	270	6.3	7.7	0.54
8	315	7.0	8.0	0.57

5. Modeling

The SPM modeling and mooring lines were done using OrcaFlex software. Six steel mooring chains

[5] Iranian Seas Wave Modeling

[6] Extreme Value Analysis

with chain type (R3S) were considered to fulfill the objectives of study. The length of each mooring line was 220 meters, 60 degrees towards each other [8]. The mooring lines were of catenary type (Figure 8).

Tables 3 and 4 present the SPM and mooring lines' specification of the modeling.

Table 3. Specifications of SPM [8]

Diameter	Height	Draft	Weight
11 [*m*]	5 [*m*]	3.3 [*m*]	250 [*tom*]

To simulate the mooring system, independent variables in OrcaFlex software (including wave height, current velocity, and chain diameter) were modified in the model and the force generated by these changes in the mooring system was calculated. The average values and standard deviations of each variable are presented in Table 5.

Wave model has been used for simulation, irregular wave and stokes' 5th theory.

In the graph below, the force value is shown in mooring line No. 1 in 100 seconds (Figure 9).

Table 4. Specifications of Mooring Line Chain [5]

Chain Size Diameter [*mm*]	Mooring Chains Beak Strength (R3S) [*KN*]	Characteristics	
		Mass [*kg/m*]	Stiffness EA [*KN*]
55.8	3065	68	314477
62.0	3737	84	388244
68.2	4464	102	469775

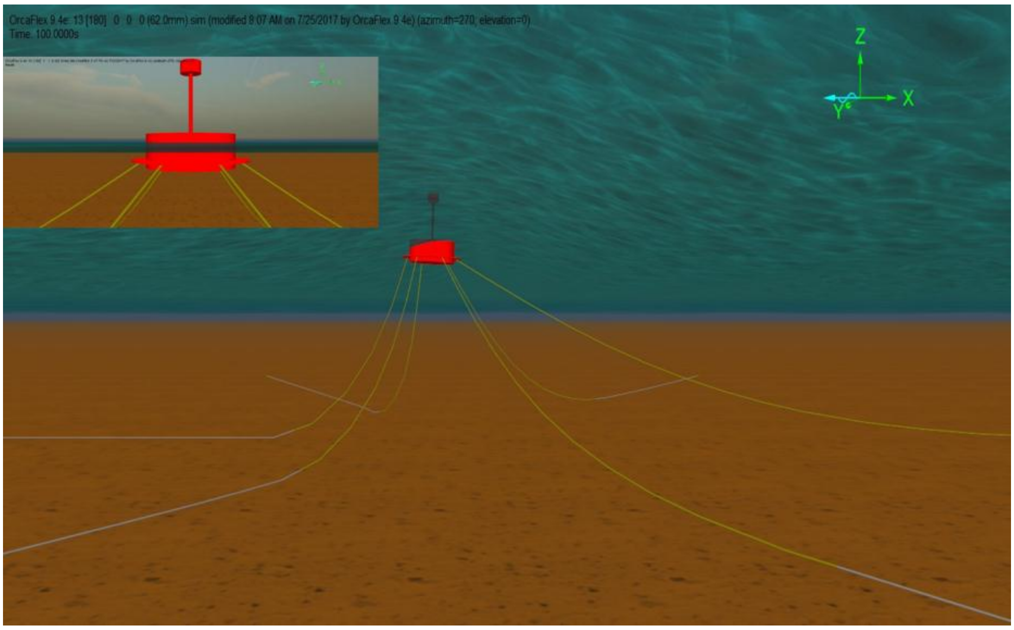

Figure 8. SPM and Mooring Lines Modeling with OrcaFlex Software [8]

Table 5. Variables in 8 Directions around the Floating Point

No.	Direction	Wave Height [*m*]			Current Velocity [*m/s*]			Chin Diameter [*mm*]		
		-1 -10%	0 0%	1 +10%	-1 -10%	0 0%	1 +10%	-1 -10%	0 0%	1 +10%
1	0	2.61	2.90	3.19	0.49	0.54	0.59	55.8	62	68.2
2	45	2.70	3.00	3.30	0.45	0.50	0.55	55.8	62	68.2
3	90	3.69	4.10	4.51	0.43	0.48	0.53	55.8	62	68.2
4	135	4.68	5.20	5.72	0.50	0.55	0.61	55.8	62	68.2
5	180	7.47	8.30	9.13	0.54	0.60	0.66	55.8	62	68.2
6	225	0.81	0.90	0.99	0.45	0.50	0.55	55.8	62	68.2
7	270	5.67	6.30	6.93	0.49	0.54	0.59	55.8	62	68.2
8	315	6.30	7.00	7.70	0.51	0.57	0.63	55.8	62	68.2

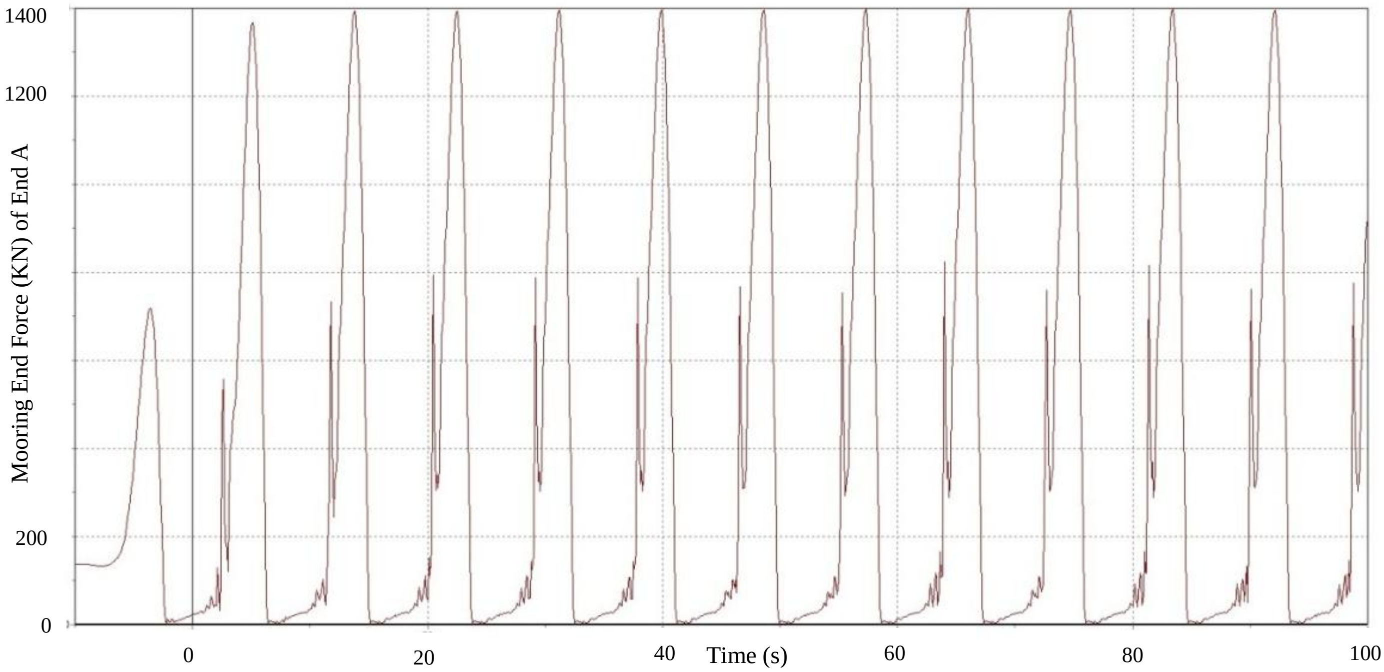

Figure 9. Force Value in Mooring Line No. 1 in 100 Seconds

Table 6. Force Values in Each Mooring due to Varying Variable Parameters at 180 Degrees

Mixed Modes	Combination Variable Parameters			Mooring Forces [*KN*]					
	Wave Height [*m*]	Current Velocity [m/s]	Chain Diameter [*mm*]	Mooring Line No1	Mooring Line No.2	Mooring Line No.3	Mooring Line No.4	Mooring Line No.5	Mooring Line No.6
1	7.47	0.54	62.0	1087.19	202.74	105.78	162.20	135.31	220.19
2	7.47	0.66	62.0	1178.89	210.34	91.20	163.33	125.98	232.90
3	9.13	0.54	62.0	1667.19	267.67	115.03	162.32	141.47	296.25
4	9.13	0.66	62.0	1769.48	277.98	134.40	189.05	150.72	306.99
5	7.47	0.60	55.8	1134.71	181.38	105.53	82.69	112.72	206.30
6	7.47	0.60	68.2	1124.18	235.51	125.20	171.48	149.94	249.24
7	9.13	0.60	55.8	1688.09	250.12	130.99	132.16	113.76	276.92
8	9.13	0.60	68.2	1745.25	297.78	191.95	260.43	189.78	322.73
9	8.30	0.54	55.8	1339.95	207.04	118.31	92.28	80.37	234.57
10	8.30	0.54	68.2	1369.35	259.24	131.56	243.96	171.50	277.54
11	8.30	0.66	55.8	1436.21	219.48	97.13	96.17	90.08	244.60
12	8.30	0.66	68.2	1462.80	266.03	133.81	220.24	152.63	290.05
13	8.30	0.60	62.0	1398.46	236.24	103.88	195.58	122.21	261.20

There are thirteen different modes of combining the variation of independent variables for each mooring line. As for these numbers, numerical analyses were performed using the OrcaFlex software to obtain an approximate relationship between these variables and the forces involved in each mooring line. The scaled values of these variables, together with the mooring force, are derived from each case in Table 6 for a 180-degree angle (direction of the maximum environmental forces).

For obtaining an approximate relation between the response surface methodologies, the response level equation, taking into account the number of discrete points in each independent variable, was considered as follows. This equation is created using the Pascal Pyramid, which is for the three variables [7].

$$F = a_{1+}a_2H + a_3V + a_4D + a_5HV + a_6HD + a_7VD + a_8H^2 + a_9V^2 + a_{10}D^2 \quad (8)$$

In this equation, D is the diameter of the mooring (in meters); V is the current velocity (in meters per second), and H is wave height (in meters), and there are 10 missing parameters by inserting the values of the independent parameters and the amount of force The results obtained in Table 6 show the linear equation with 10 unknowns for each mooring and in eight directions for applying environmental forces. By inserting the force values and the related parameters, the unknown coefficients of equation (8) are obtained. For example, for mooring line no. 1 and taking forces along the 180 degree angle, the values of coefficients "a_i" are obtained as follows.

By mapping independent variables into U, the relationship between independent variables and U_i variables is obtained in equation (9) [6].

$$\mathbf{U} = (U_{\boldsymbol{D}}, U_{\boldsymbol{L}}, U_{\boldsymbol{\theta}}) = \left(\frac{D-\mu_D}{\sigma_D}, \frac{L-\mu_L}{\sigma_L}, \frac{\theta-\mu_\theta}{\sigma_\theta}\right) \quad (9)$$

or it can be shown as equation (10):

$$(D, L, \theta) = (\mu_D + U_1\sigma_D, \quad \mu_L + U_2\sigma_L, \quad \mu_\theta + U_3\sigma_\theta) \quad (10)$$

Inserting these values and the mean values and standard deviations of each variable in the mooring force relationship, the failure force $g(U_1, U_2, U_3)$ is obtained by equation (11).

$$g(U_1, U_2, U_3) = \text{Ultimate Forces} - \text{Mooring Forces} \quad (11)$$

Table 7. The Values of Coefficients "a_i" for Mooring Line No. 1 for Forces of 180 Degrees Direction

No.	Coefficients	Quantity
1	a(1)	2518.65
2	a(2)	-463.48
3	a(3)	-566.62
4	a(4)	-25689.81
5	a(5)	53.23
6	a(6)	3288.28
7	a(7)	-1888.32
8	a(8)	34.99
9	a(9)	867.72
10	a(10)	12897.36

To calculate the reliability of the FORM method and to find the target point, the function $g(U_1, U_2, U_3)$ from MPP is used.

Using the program written in MATLAB software, the value of β and other reliability parameters are calculated, for which values are obtained for six mooring lines and eight directions for the environmental forces. Table 8, the reliability index is calculated for mooring line No. 1 to mooring line No.6.

It can be clearly seen that the most probable failure of the mooring line No.1 occurs at an angle of 180 degrees of environmental force. The reason for this is that the maximum force of the perimeter extends along the 180 degrees and is in line with the mooring line No.1.

According to DNVGL-OS-E301 [4], and given that the reliability index (β) is greater than 3.09 and the probability of failure (p_f) is less than 1×10^{-3}, the safe operation of the mooring lines is subject to changes in environmental loads and geometry, based on the assumptions of the study.

Table 8. Values of Reliability Parameters for Mooring Line No. 1 to Mooring Line 6

Mooring Line No.1

Direction [*degree*]	Reliability Index [β]	Reliability [*R*]	p_f [*1-R*]
0	6.48	0.99999999995	4.55E-11
45	6.54	0.99999999997	3.09E-11
90	6.49	0.99999999996	4.32E-11
135	6.11	0.99999999949	5.08E-10
180	3.51	0.99977762106	2.22E-04
225	6.40	0.99999999992	7.81E-11
270	6.33	0.99999999987	1.26E-10
315	6.50	0.99999999996	4.03E-11

Mooring Line No.2

Direction [*degree*]	Reliability Index [β]	Reliability [*R*]	p_f [*1-R*]
0	6.51	0.99999999996	3.71E-11
45	6.40	0.99999999992	7.65E-11
90	6.57	0.99999999998	2.48E-11
135	6.49	0.99999999996	4.44E-11
180	6.31	0.99999999986	1.43E-10
225	6.31	0.99999999986	1.43E-10
270	5.35	0.99999999934	4.37E-08
315	6.50	0.99999999996	3.97E-11

Mooring Line No.3

Direction [*degree*]	Reliability Index [β]	Reliability [*R*]	p_f [*1-R*]
0	6.43	0.99999999993	6.25E-11
45	6.52	0.99999999996	3.62E-11
90	6.09	0.99999999944	5.55E-10
135	6.47	0.99999999995	4.89E-11
180	5.72	0.99999999466	5.35E-09
225	6.49	0.99999999998	4.23E-11
270	5.63	0.99999999074	9.26E-09
315	5.01	0.99999973104	2.69E-07

Mooring Line No.4

Direction [*degree*]	Reliability Index [β]	Reliability [*R*]	p_f [*1-R*]
0	6.04	0.99999999924	7.60E-10
45	6.35	0.99999999989	1.07E-10
90	6.62	0.99999999998	1.77E-11
135	6.48	0.99999999995	5.32E-11
180	6.51	0.99999999996	3.68E-11
225	6.50	0.99999999996	3.89E-11
270	6.52	0.99999999997	3.41E-11
315	6.10	0.99999999946	5.43E-10

Mooring Line No.5

Direction [*degree*]	Reliability Index [β]	Reliability [*R*]	p_f [*1-R*]
0	6.42	0.99999999993	6.61E-11
45	6.00	0.99999999901	9.87E-10
90	6.07	0.99999999934	6.57E-10
135	6.46	0.99999999995	5.16E-11
180	6.57	0.99999999998	2.48E-11
225	6.43	0.99999999993	6.26E-11
270	6.08	0.99999999939	6.14E-10
315	6.53	0.99999999997	3.36E-11

Mooring Line No.6

Direction [*degree*]	Reliability Index [β]	Reliability [*R*]	p_f [*1-R*]
0	6.47	0.99999999995	5.01E-11
45	6.49	0.99999999996	4.17E-11
90	5.92	0.99999999837	1.63E-09
135	6.17	0.99999999965	3.51E-10
180	6.25	0.99999999980	2.05E-10
225	6.50	0.99999999996	4.08E-11
270	6.34	0.99999999989	1.14E-10
315	6.46	0.99999999995	5.19E-11

6. Summary and Conclusions

- The results show that as the diameter of the mooring increases, the force applied to the mooring increases, and this increase in diameter increases the weight of the mooring and therefore the cost of the project. Thus, it is necessary to consider optimum mooring diameter for designing both cost-effective and technical line based on computational and related standards of mooring design.
- The results of this study revealed that the increase in the diameter of the chain mooring increases the mass of the mooring system and decreases the SPM movement.
- Regarding the amount of wave and current, it can be stated that the higher the amount of wave and current characteristics get, the greater the force applied to the mooring will be. In moorings that are in line with the maximum forces generated by the wave and current, there would be greater response compared to the non-aligned mooring lines with these environmental forces.
- In order to perform the reliability analysis, three variables of chain diameter, current velocity and wave height were used. The range of changes in variables was considered 10%. Also, environmental forces were considered in eight directions with a return period of 100 years to assess reliability. The results demonstrated that the mooring system had an appropriate reliability and reliability index and with the assumptions it intended to change the variables. It was also found that the probability of failure in the mooring system was low.
- The most likely failure of the mooring line no.1 occurred at an angle of 180-degrees of environmental force. The reason is that the maximum force of the peripheral force was along 180-degrees and in line with the mooring line No.1.
- According to the results, the reliability index for the floating control lines was greater than 3.51, indicating the safe operation of the mooring lines under changes in the environmental loads and geometry.
- It is observed that the mooring lines in the direction of lower environmental forces are more reliable and the probability of their failure is very low, while; the moorings that are in line with the maximum environmental forces have lower reliability index, and they are more likely to be damaged compared to other mooring lines.

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