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Global Analysis of a Flexible Riser

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Abstract: The mechanical performance of a flexible riser is more outstanding than other risers in violent environmental conditions. Based on the lumped mass method, a steep wave flexible riser configuration attached to a Floating Production Storage and Offloading (FPSO) has been applied to a global analysis in order to acquire the static and dynamic behavior of the flexible riser. The riser was divided into a series of straight massless line segments with a node at each end. Only the axial and torsional properties of the line were modeled, while the mass, weight, and buoyancy were all lumped to the nodes. Four different buoyancy module lengths have been made to demonstrate the importance of mode selection, so as to confirm the optimum buoyancy module length. The results in the sensitivity study show that the flexible riser is not very sensitive to the ocean current, and the buoyancy module can reduce the Von Mises stress and improve the mechanical performance of the flexible riser. Shorter buoyancy module length can reduce the riser effective tension in a specific range of the buoyancy module length when other parameters are constant, but it can also increase the maximum curvature of the riser. As a result, all kinds of the riser performances should be taken into account in order to select the most appropriate buoyancy module length.
Keywords: flexible riser; lumped mass method; global analysis; sensitivity study
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1 Introduction

Due to the effect of the ocean environment on ocean platforms, the motion characteristics are of diverse kinds, and there are various requirements for the riser systems. The capability of a flexible riser is different from other risers because of its special structure, which consists of several layers of different materials. It is superior to other kinds of risers because of its larger bending capability, and it can be applied to more undesirable environmental conditions.

Flexible risers are slender marine structures which are widely used in deepwater exploration and also to deliver oil and natural gas from the subsea to surface units. In deep-water applications, because of the low bending stiffness compared to axial and torsional stiffness, flexible risers can suffer large displacements, causing them to demand geometrically special nonlinear analysis (Kordkheili and Bahai, 2007).

Flexible risers have many arrangement forms (Bai and Bai, 2005), such as Free Hanging Catenary, Lazy Wave, Steep Wave, and Pliant Wave (lazy S, Steep S). Based on the lumped mass method, Wang and Chen(1991) established a non-linear element dynamic analysis method considering the flowing of fluid in a pipe, and the results were compared to former outcomes (Wang and Chen, 1991). Bahtui *et al.*(2008) accomplished a detailed finite element analysis of unbonded flexible risers using ABAQUS, and made a comparison between the numerical results and the analytical solution ones (Bahtui *et al.,* 2008). Zhimin Tan, Peter Quiggin and Terry Sheldrake presented a "state-of-the-art" dynamic simulation in time domain of the 3D bending hysteresis behaviors of a flexible riser under offshore environment loads (Tan *et al.*, 2009). Based on the Algorithmic Processor Description Language (APDL), Jifang Zeng realized the program and atomization modeling (Zeng, 2009).

As a lot of detailed and local analysis has been completed by the anterior studies, this paper adopts the lumped mass method to perform global analysis on the flexible riser; furthermore, the ocean wave and current loads are simplified in order to represent the static and dynamic response better under the effect of an ocean environment.

2 Mechanical model of a flexible riser

Based on the lumped mass method, OrcaFlex is used to simulate the flexible riser. The analysis is based on the following assumptions: (1) Geometric property and material characteristics of the flexible riser units are constant. (2) The bottom end of the riser is completely constrained in all directions and rotations. (3) Considering the effect of the deadweight and the external load of the riser, the analysis belongs to the category of small strain and large deformation issues (Zhong, 2007). (4) The Stokes 5th wave is used to simulate the motion of the platform to act as the boundary condition at the top end of the riser.

2.1 The load modeling

In the presence of waves, the current must be extrapolated above the still water level. In this paper it is assumed that the

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surface current applies to all levels above the water surface.

Current direction is specified and does not vary with depth. Speed varies with position (*X*, *Y*, *Z*) according to the formula as follows:

$$S = S_t + (S_s - S_t) \times ((Z - Z_t)/(Z_s - Z_t))\wedge(1/Ex)$$

where S_S and S_t are the current speed on the surface and seabed, *Ex* is the power law exponent, Z_S is the water surface of the *Z* level, all as specified in the data, and Z_t is the *Z* level of the seabed directly below (*X*,*Y*).

To calculate the current load, an extended form of Morison's equation has been used. Morison's equation was originally formulated for calculating the wave loads on fixed vertical cylinders. There are two force components; one is related to water particle acceleration (the 'inertia' force) and the other related to water particle velocity (the 'drag' force).

The extended form of Morison's equation used in this paper is:

$$F_W = (\Delta \cdot a_w + C_a \cdot \Delta \cdot a_r) + \frac{1}{2}\rho \cdot V_r |V_r| C_D \cdot A$$

In the formula, F_W is the wave force, Δ is the mass of fluid displaced by the body, a_w is the fluid acceleration relative to earth, C_a is the added mass coefficient for the body, a_r is the fluid acceleration relative to the body, ρ is the density of water, V_r is the fluid velocity relative to the body, C_D is the drag coefficient, and *A* is the drag area. The term in parentheses is the inertia force, and the other is the drag force. In flexible riser analysis, C_D varies between 0.7 and 1.2.

2.2 Boundary condition

The top of the riser was attached to an FPSO, using the response amplitude operator (RAO) of the FPSO as the boundary condition at the top end of the riser. The bottom end of the riser is fixed to the seabed; the seabed friction is not considered here. It is very important to obtain accurate values of the RAO amplitude and phase if the dynamics of the system are to be correctly modeled.

The model of the flexible riser is shown in Fig.1. Also, the fixed bend stiffener at the lower end is modeled as two elastic solid blocks with no rotation, which are connected at their interface. The turret at the top end is modeled as an elastic solid cylinder connected to the FPSO.

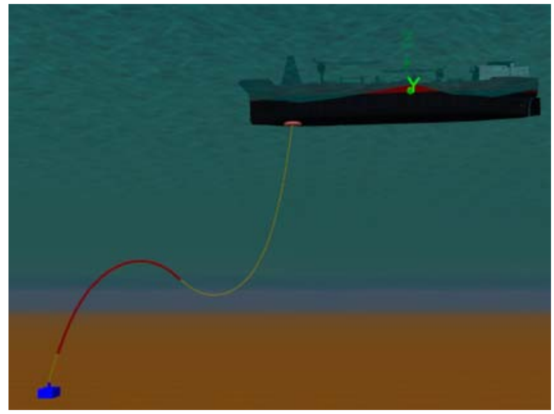
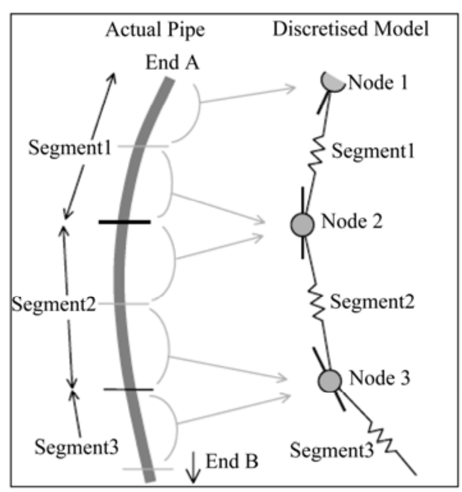


Fig.1 Model of the flexible riser

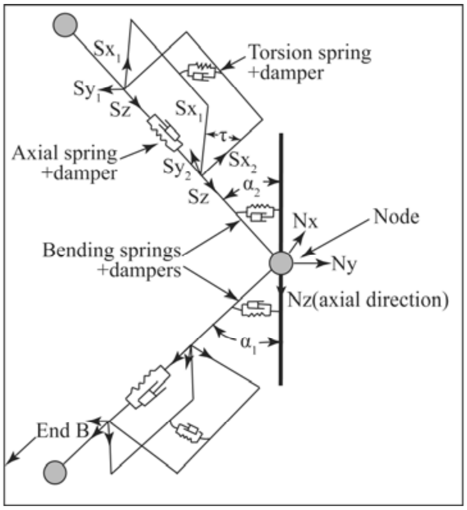
2.3 Building the model of the flexible riser

Using OrcaFlex to simulate the flexible riser, the bottom end of the riser is completely constrained in all directions and rotations, and the Stokes 5th wave is applied to the platform. The displacement of the connection point between FPSO and riser is taken as the boundary condition at the top end of the riser. As the dynamic performance of the flexible riser is geometrically non-linear, the results of the frequency domain analysis are not accurate; time domain analysis is commonly used to analyze the performance of flexible riser.

Based on the lumped mass method, the riser is modeled as a line, which is divided into a series of line segments. The line segments only model the axial and torsional properties of the line. The other properties (mass, weight, buoyancy, *etc*.) are all lumped to the nodes. The lumped mass model is shown in Fig.2 (OrcaFlex User Manual).



(a) Line model



(b) Detailed representation of Line model

Fig.2 The theory of the lumped mass method

3 Global analysis

Global analysis of the flexible riser is performed to evaluate the global load effects on the riser. In order to evaluate the performance of the riser, the static configuration and extreme response of displacement, curvature, force, and moment from environmental effects should be calculated in the global analysis.

The global analysis includes two aspects: static analysis and dynamic analysis. The static analysis can determine the equilibrium configuration of the system under weight, buoyancy, and drag force. Additionally, it can also provide a starting configuration for dynamic analysis. In most cases, the static equilibrium configuration is the best starting point for dynamic analysis. The dynamic analysis is a time simulation of the motion of the model over a specified period of time, starting from the position derived by the static analysis.

The environment defines the conditions to which the objects in the model are subjected, and it consists of the current, waves, and seabed. The operating water depth is 91.5m, while the influence by the change of tide has not been considered. The wave height is 7.3m, and the wave period is 11 seconds. The current data is shown in Table 1.

Table 1 The current velocity of 3 different return periods

X/H	1 year return /m·s^{-1}	10-year-return /m·s^{-1}	100-year-return /m·s^{-1}
0.1	1.22	1.75	2.24
0.5	0.91	1.24	1.49
0.9	0.77	0.99	1.17

The fundamental parameter of the riser is shown in Table 2. The flexible riser has a fixed bend stiffener at the lower end and a sliding bend stiffener at the upper end. The in-built angle of the flange on the connecting pipe, which is running through the turret, is 15 degree from the vertical, while the in-built angle at the pipeline end manifold (PLEM) is 20 degree from vertical. The buoyancy elements will be clamped to the flexile riser over a length of 70 m, starting from a point 10 m away from the lower end of the riser.

Table 2 The fundamental parameters of the riser

case	value
Total length	185m
Pipe inner diameter	0.3048m
Pipe overall diameter	0.4884m
The density of riser material	242.5kg/m
Design pressure	55.0 barg
Design temperature	87.0 ℃
Bending stiffness at 20 ℃	390 kNm^2
Axial tensile stiffness	907 MN
Torsional stiffness	224KNm^2/deg
Relative gravity	1.26
Per Buoyancy Module Weight	674.6kg
mud density	780kg/m

The fundamental parameter of the FPSO is shown as follows. The RAO of the FPSO is used as the boundary condition at the top end of the riser, considering the interaction between the FPSO and flexible riser. The RAO is obtained from hydrodynamic calculation.

Table 3 The fundamental parameters of the FPSO

Length overall /m	285m
Breadth./m	63m
Depth moulded /m	32m
Draft (Fully loaded)./m	24.45m
Topside weight (operational)./ t	35,860
Mooring system	the single point mooring

4 The results and discussion

4.1 The static analysis

The aim of static analysis is to determine the initial static geometry of the flexible riser configuration. The design parameters to be selected in the static analysis are typically length, weight, buoyancy requirements, and location of seabed touchdown point and subsea buoy. The loads considered in the static analysis stage are generally gravity, buoyancy, internal fluid, and current loads.

After the static analysis, the Z-axis coordinate of the flexible riser is shown in Fig.3.

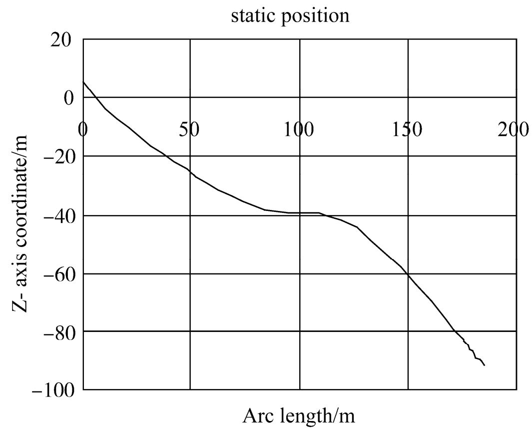


Fig.3 The *Z*- axis coordinate of the flexible riser

Under the effect of the current load, the effective tension of the flexible riser changed along the arc length of the riser. From Fig.4, it is shown that the effective tension changes along the arc length of the flexible riser and there is almost no difference among the three curves. It could also be found on the segments with the buoyancy module that the effective tensions are almost the same under different return periods of the current. Therefore, it turns out that the buoyancy module can change the uptrend of effective tension, and improve the mechanical performance of the flexible riser.

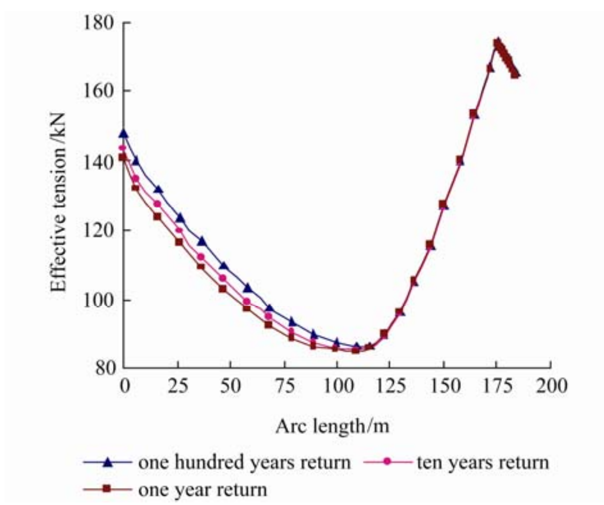


Fig.4 The effective tension in static analysis

4.2 Dynamic analysis

The dynamic analysis primarily represents the analysis of the riser response to the combined action of the wind, wave, and current. The starting point for dynamic simulation is the static equilibrium configuration. Dynamic simulation considers the RAO of the FPSO over a specified period of time. Three kinds of current loadings are selected: a one year return, ten-year return, and one-hundred-year return. The FPSO motion is decided by the wind and wave according to the wave height, water depth, and wave period. The RAO is used to represent the motion of the FPSO, which acts as the boundary condition at the top end of the riser, and then to carry out the dynamic analysis.

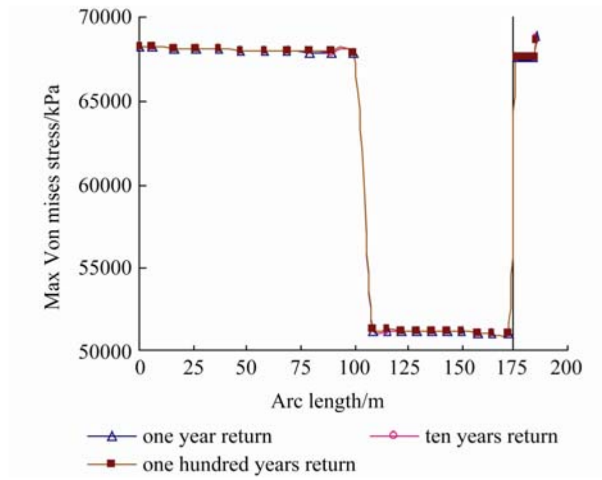


Fig.5 The Von Mises stress along the riser in static analysis

Fig.5 presents the Von Mises stress of the riser under the dynamic analysis. The segment from 105 to 175m has a buoyancy module, while other segments do not have a buoyancy module. The Von Mises stress changed sharply at the two points where the structure changed. It can be seen that the Von Mises stresses of the segments with the buoyancy modules are less than that of the segments without a buoyancy module. That is because the stress of the segments equipped with the buoyancy module will be different from the ones without a buoyancy module. The curves of Von Mises stress under three different return periods of the current conditions are very similar. It is obvious that the influence of current on the flexible riser is not very distinct in very shallow water. The maximum Von Mises stress value of the riser is 68.5MPa, which is in the range of the design pressure. Under the effects of these three kinds of currents, the Von Mises stress of the riser is almost the same; it can also be seen that the flexible riser is not very sensitive to the ocean current.

Fig.6 shows the effective tension of the riser. The effective dynamic tension is different from the static analysis result. In the static analysis, the effective tension at the bottom end of the riser is larger than at the top end, but it is the opposite in the dynamic analysis. In addition, the effective dynamic tension is larger than the effective static tension. The value of effective tension under the one-hundred-year return period current condition is maximum, and the effective tension under the one-year return period condition is minimum. The effective tension is relatively large in the area of the riser top and bottom, to which more attention should be given.

Table 4 The minimum bend radius of the flexible riser

Currents	Minimum bend radius /m
One year return period	22.43
Ten years return period	27.82
One hundred years return period	31.84

Fig.7 shows the bend radius of the riser on three different current conditions. The minimum bend radii of the flexible riser on the three different current conditions are listed in Table 4, and they are all smaller than the designed minimum ones, making them safe. However, the bend radius has an abrupt change in the position of the riser where the structure also has an abrupt change. For the three different currents, the bend radii of the riser segment which has a buoyancy module are almost the same.

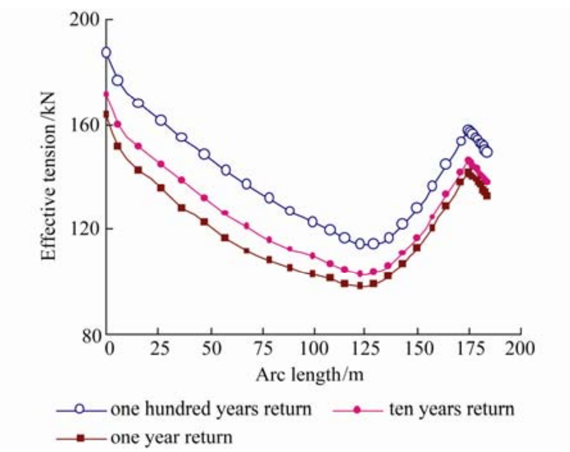


Fig.6 The effective tension of the flexible riser on three different kinds of current conditions in dynamic analysis

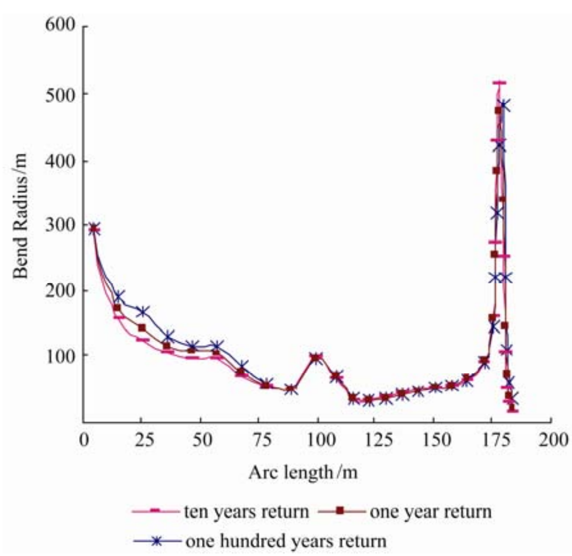


Fig.7 The bend radius of the flexible riser on three different current conditions in dynamic analysis

Table 5 The minimum and maximum curvatures of the flexible riser

Currents	Minimum curvature/ $1 \cdot m^{-1}$	Maximum curvature/ $1 \cdot m^{-1}$
One year return period	0	0.04
Ten years return period	0	0.027
One hundred years return period	0	0.024

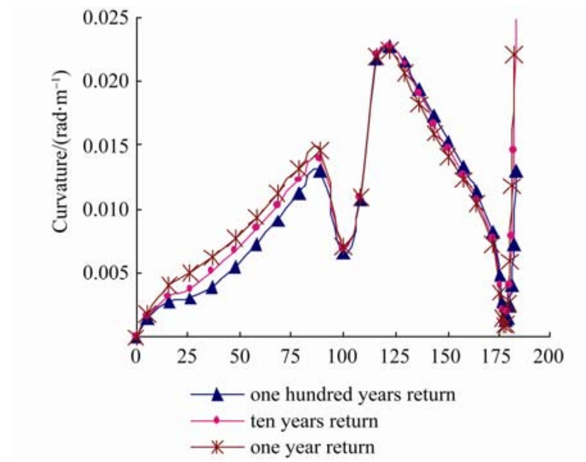


Fig.8 The curvature of the flexible riser on three different current conditions in dynamic analysis

The curvatures of the riser under three different currents are shown as Fig.8. The minimum and maximum curvatures of the riser on three different current conditions are listed in Table 5.

The three curves are almost the same, only differing in the areas ranging from 0 to 100m and 125m to 185m along the arc length of the riser. The riser segments from 0 to 100m are bare, without the buoyancy module; the maximum curvature in the case of the one-hundred-year return period current is minimum, while the value on the one-year return period current condition is the biggest. The riser segments from 125m to 185m are wrapped with a buoyancy module, and the maximum curvature value in the case of the one-hundred-year return period current is the biggest, while on the one-year return period current condition it is minimum. It is clear that the buoyancy module has an effect on the mechanical performance of the riser. The buoyancy module makes the riser less sensitive to the current load.

Fig.9 presents the same trend for the bending moments as Fig.8 for the curvature on three current conditions, because the bending moment is related to the curvature.

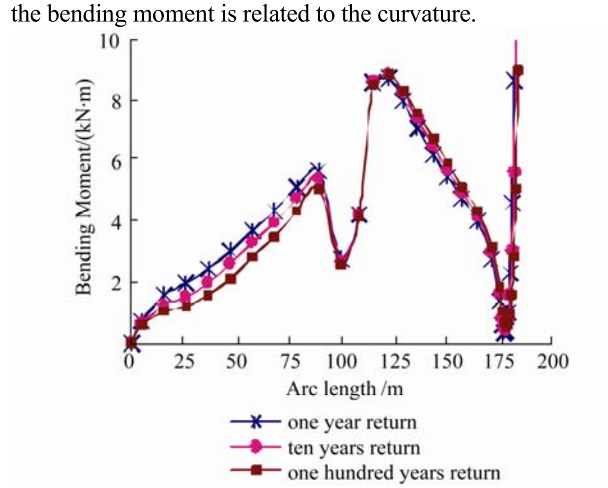


Fig.9 The bending moment of the flexible riser on three different current conditions in dynamic analysis

4.3 Sensitivity study

The buoyancy module length of the riser is a significant parameter, for it can influence the riser dynamic performance. In this paper, the main objective of the sensitivity study is to obtain the effect of the length of buoyancy module equipped on the mechanical performance of the riser. A series of buoyancy module lengths are selected to be used in the calculation. At the same time, the results are verified based on the recommended practice of API 17J and API RP 17B to achieve a reasonable length of the buoyancy module. After calculation, it can be seen that the buoyancy module length can vary from about 50 to 100m. The riser structure can hardly be supported without buoyancy if the equipped buoyancy module length is shorter than 50m. And if the equipped buoyancy module length is longer than 100m, the maximum curvature of the riser can't meet the requirements of recommended practice.

So the equipped lengths of buoyancy module adopted in this study are 57, 70, 83, and 96m, respectively. The riser equipped with the 57m buoyancy module has 16 buoyancy modules, and the one equipped with the 70m buoyancy module has 19 buoyancy modules. The one equipped with the 83m buoyancy module has 22 buoyancy modules, and the one equipped with the 96m buoyancy module has 25 buoyancy modules.

The results of the static and dynamic analysis on the one-hundred-year return period current condition for the risers are shown from Figs.10 to 12.

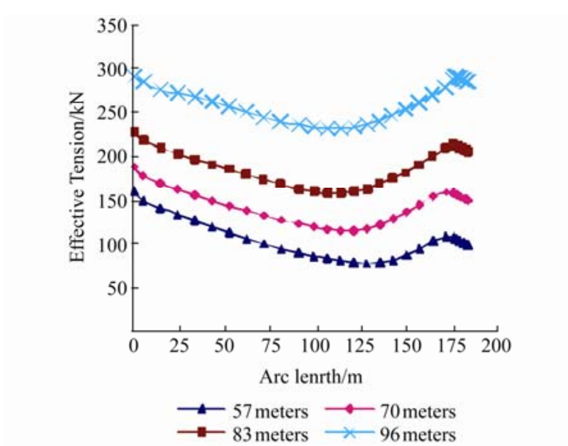


Fig.10 The effective tension of the four risers in dynamic analysis

Fig.10 to Fig.12 respectively show the effective tension, bending moment, and the bend radius of the four risers after dynamic analysis. The trends of the four curves are almost the same in each figure; the riser with the 96m buoyancy module gets the biggest effective tension, while the effective tension of the riser with the 57m buoyancy module is the smallest. For effective tension, the buoyancy module length is not better when shorter; it falls in a specified range. For the bending moment, all the four curves have two peak values; the first one appears in the vicinity of about 10m above the top of the buoyancy module, and the second one appears in an area about 15m under the top end of the buoyancy module. The peak value of the riser which has the 57m buoyancy module is lager than others, and the peak value of the riser with the 96m buoyancy module is the smallest.

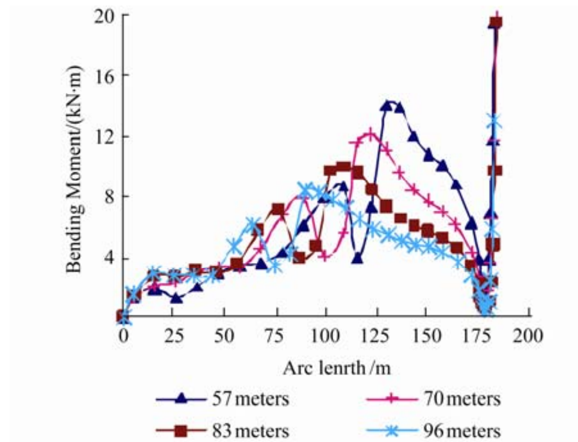


Fig.11 The bending moment of the four risersin dynamic analysis

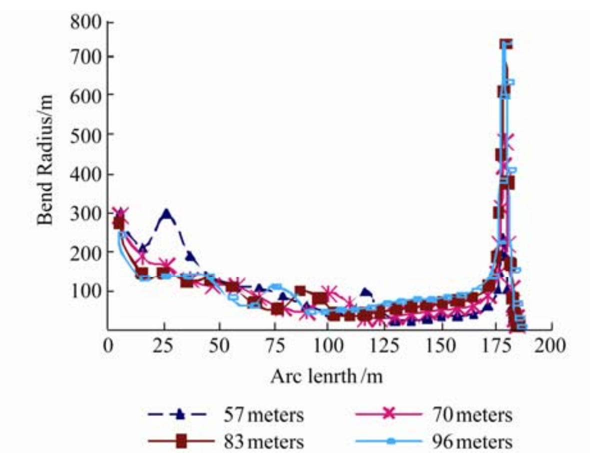


Fig.12 The bend radius of the four risers in dynamic analysis

Fig.12 shows the bend radius of the four risers. The minimum bend radius values of the four risers are listed in Table 6. The value gradually becomes larger from the riser with the 57m buoyancy module to the one with the 96 m buoyancy module. When other parameters are constant, increasing the equipped length of buoyancy module can enhance the minimum bend radius of the riser.

Table 6 Minimum bend radius of the four risers

Buoyancy module length of the riser /m	Minimum bend radius /m
57	27.82
70	32.22
83	39.25
96	46.42

5 Conclusions

Based on the lumped mass method, global analysis of the flexible riser has been made. A simplification has also been performed on the ocean wave and current load. The model of a flexible riser has been built in order to analyze the dynamic response of the riser on three different current conditions. The effect of the buoyancy module length of the riser has also been considered in this study. The results show that, the flexible riser is not very sensitive to the ocean current, and the buoyancy module can reduce the Von Mises stress while improving the mechanical performance of the flexible riser. Also, the bending moment is relative to the curvature. In general, an abrupt change of the structure can induce an abrupt change of the mechanical performance.

A comparison of results of the four risers with different length of buoyancy modules demonstrates the importance of module length selection. When other parameters are constant, increasing the buoyancy module length can enhance the minimum bend radius of the riser, and it can also reduce the bending moment. However, that is not always reasonable, for it works in a specified range of buoyancy module length. An extremely long or short buoyancy module will weaken the mechanical behavior of the riser.

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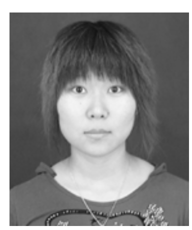

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