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Dynamic Behavior of the Deepwater Flexible Pipeline during Pipe Laying Process

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Abstract: The dynamic behavior of the flexible pipeline during deepwater Flex-lay directly determines the structures of laying facilities and the actual installation process. A coupled dynamic model considering the effects of different factors was established in this paper. Based on the model, the initial attitude of the flexible pipeline during the laying process was determined by using the natural catenary theory and Morison equation. The hydrodynamic analysis of the HYSY201 pipelaying vessel was carried out by using the finite element software AQWA. Under the specific sea condition, a flexible pipeline with outer-diameter of 352.42 mm being laid onto the 3000 m deep seabed was simulated by using the software OrcaFlex to study the pipeline dynamic behaviors including axial tension, bending moment and stress-strain in the laying process, and the factors affecting the dynamic behavior of the pipeline were analyzed. The results show a significant correlation between the marine loads, vessel motion and the dynamic response of the pipeline. Compared with the static state case, the maximum axial tension, bending moment and stress-strain of the pipeline under the interaction of the marine loads and the vessel motion increased by 42.7%, 220%, 52% and 18.7%, separately. Among the marine loads, the surface wave had the most significant effect on the dynamic performance of the pipeline. When the wave direction acts on the width of the ship, the wave height is greater than 2 m and the spectrum period is eight seconds, the wave has the greatest influence on the dynamic response of the pipeline.

Keywords: flexible pipeline; flex-lay; pipelaying vessel; sea state; dynamic behavior

1. Introduction

With the gradual development of oil and natural gas exploration in various countries, the proportion of offshore oil and natural gas resources is increasing. Submarine pipeline transportation is the main mode of marine oil and gas transportation, which has obvious advantages in terms of efficiency, economy and reliability [1,2]. Compared with rigid pipeline, flexible pipeline has significant advantages, so it is also widely used in drilling risers, production risers, export risers and workover risers [3]. As the exploration of the oil field is entering deepwater or ultra-deepwater areas, the main application of the Flex-lay system will confront greater challenges [4].

Due to the wide application of flexible pipes, a Flex-lay method for laying flexible pipes has appeared, its laying principle is similar to that of the Reel-lay method. Flexible pipes are reeled in the drum and unreeled into the sea through the laying system in the construction area [5,6]. Compared with other pipe laying methods, the Flex-lay method has a wider range of water depth and higher laying efficiency. Meanwhile, the curvature of the flexible pipe is smaller, which reduces the size and weight of the whole laying system and makes it easier to carry on the vessel. The dynamic behavior of the pipeline has direct influence on the working load of the pipeline laying system, which is an important design index of the laying tower system. In the actual process of pipeline laying, the dynamic behavior of the pipeline will be affected by factors such as ocean load and vessel motion. Therefore, it is of great significance for the design of flexible pipe and laying system to study the pipeline dynamic behavior and its influencing factors under the action of ocean loads.

The analysis methods of pipeline laying process mainly include static and dynamic analysis [7]. Static analysis is used to analyze the discontinuous laying mode to analyze the attitude and stress of the laid flexible pipeline. Based on the elastic rod theory, the static equilibrium formula of submarine pipeline was derived by using perturbation method, and the nonlinear problem of submarine pipeline was solved by Konuk [8]. Lenci, S. simplified the J-lay laying problem, and compared it with the classical catenary theory to prove its applicability in deepwater and ultra-deepwater installation [9]. In order to solve the attitude and stress of S-lay pipeline in deep water, Brownnr put forward a solution method which ignores the pipeline stiffness bases of catenary theory, and the calculation results had high accuracy and efficiency [10]. Based on the static analysis, the dynamic analysis incorporates the interaction of environmental loads and the vessel motion to analyze the dynamic response of the flexible pipeline. In order to achieve constant tension in the laying of the pipeline laying system, Brewer analyzed the sensitivity of the pipeline tension in the deepwater [11]. Jasnapo et al. established the dynamic control equation of the submarine flexible-cable laying system based on the principle of d'Alembert, and analyzed the dynamic problems caused by the interaction between the flexible cable and the laying vessel [12]. Santillan et al. established a balance equation, considering the influence of platform motion and the vibration sensitivity on the flexible pipeline, and the results showed that increasing the riser buoyancy can reduce the axial force of the pipeline, which was verified by the simulation experiment [13]. Based on the principle of mass flow, Hong proposed a method to build a slender offshore equipment model. The absolute node formula is used to analyze the large displacement and angle structure of submarine pipeline, then the system control equation based on the principle of d'Alembert is established [14]. Gong and Zan et al. established the coupling model of the laying process of the deepwater S-lay system by using software OrcaFlex, and studied the ship motion and the dynamic behavior of the pipeline in the coupling model [15,16]. Wang established the theoretical model of subsea manifold installation based on the small deformation theory, and studied the dynamic characteristics of drill pipe in different installation stages of subsea manifold installation [17].

Past studies on the laying of submarine pipelines mostly focused on the S-lay and J-lay method for laying rigid pipelines, while few studied the dynamic behavior of flexible pipelines. Therefore, this paper uses flexible pipelines as the research object to study the dynamic behavior of the pipeline during the process of Flex-lay. A coupling model for Flex-lay is established, which mainly includes vessel motion, marine loads and pipeline dynamic model. The marine loads of the fourth-level sea condition is analyzed. The static tension and attitude of the pipeline are determined by using the catenary theory combined with the Morison hydrodynamic equation. The ANSYS-AQWA software is used to determine the relevant parameters of the pipelaying vessel HYSY201 as the analysis object. Finally, a comprehensive finite element model for Flex-lay was established by using Orcaflex software and used to carry out an illustrative example analysis of a 10-inch flexible pipeline being laid onto the seabed with a water depth of 3000 m. Finally, the influence of various factors of the marine environment on the dynamic behavior of the flexible pipeline was discussed.

2. Mechanical Model

2.1. Basic Assumptions

In actual engineering, the dynamic behavior of the pipeline will change due to different flexible pipelines, marine environments and installation conditions. The laying process of placing the pipeline safely on the seabed is very complicated. The pipeline is affected by various factors, such as water depth, current, waves and the irregular moment of vessel in the marine environment. In order to simplify the model of flexible pipeline laying analysis, the following assumptions are proposed:

(1) The marine loads in the model are assumed to be the ideal loads, and the seabed is simplified to a horizontal seabed with a constant stiffness;

(2) The direction of ocean currents and the deformation of the flexible pipeline are assumed to lie in the same plane, and the speed of currents in the seabed is zero and the speed is the maximum in the sea surface;

(3) Under the random marine loads, the torsional deformation of the flexible pipe is very small, so the torsional deformation of the flexible pipe is ignored in the dynamic analysis, and the impact of the Flex-lay system contact with the flexible pipe on the bending stiffness is ignored;

(4) In the mechanical analysis, the flexible pipe with a multi-layer structure is assumed to be a continuous pipe with uniform material and isotropy;

(5) The effects of laying systems in contact with flexible pipes on pipe bending stiffness is ignored.

2.2. Equations for Coupled Model

As the depth of the laying water increases, the impact of wind, current and waves on the flexible pipeline will become more obvious, and the dynamic behavior of the flexible pipeline will become non-negligible [18]. During the laying process of Flex-lay, flexible pipelines, the laying vessel, the laying structure and the ocean constitute a general Flex-lay system. The dynamic behavior of the flexible pipeline is affected by many factors in the system. It can be observed from Figure 1 that the flexible pipe is released from the reel through the Flex-lay system to adjust the direction of the pipe, and is clamped into the water by the tensioner. Under the combined action of marine loads and the laying vessel motion, the pipeline will gradually form the attitude shown in the figure. The pipeline can be divided into a suspended part, a sag bend region and a laid part, and the attitude of the pipeline is determined by the tension force, the linear density of the pipeline and the laying angle.

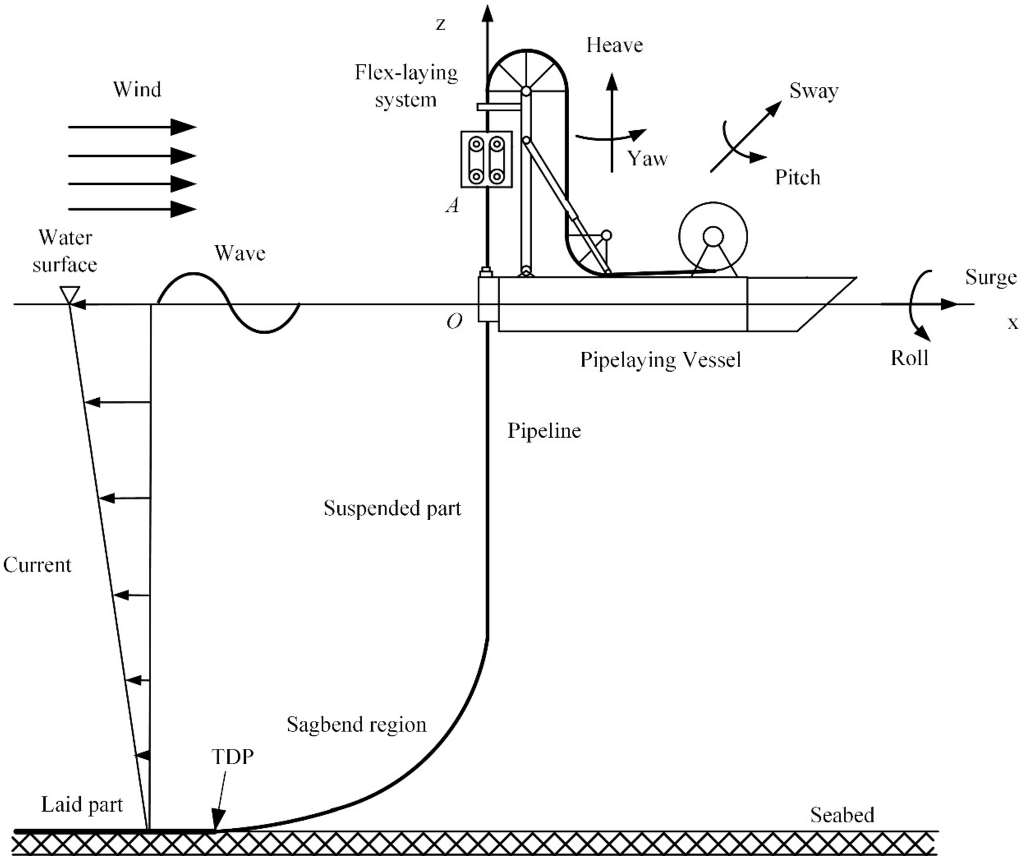


Figure 1. Schematic diagram of Flex-lay pipeline installation.

Based on the coordinate system of the Flex-lay system, then applying Newton's second law, the dynamic equation of the system can be obtained as:

$$\boldsymbol{M}\ddot{\boldsymbol{X}}(t)+\boldsymbol{C}\boldsymbol{X}(t)=\boldsymbol{f}_{rad}(t)+\boldsymbol{f}_{wave}(t)+\boldsymbol{f}_{c}(t)+\boldsymbol{f}_{w}(t)+\boldsymbol{f}_{p}(t) \tag{1}$$

where $\boldsymbol{M}$ denotes the inertia matrix, $\boldsymbol{C}$ is the hydrostatic restoring matrix, $\boldsymbol{X}(t)$ represents the displacement matrix of the vessel motion, t represents time, $f_{rad}(t)$ represents the radiation forces due to changes in fluid momentum caused by vessel motion, $f_{wave}(t)$ represents the wave load, $f_w(t)$ and $f_c(t)$ represent wind load and current load in the marine environment respectively, $f_p(t)$ indicates the tension of the pipeline at the tensioner position.

2.3. Pipelay Vessel Motion

Due to the superposition of forced swaying caused by the marine environment and the inherent swaying of the vessel, vessels perform complex compound movements at sea. Under the combined action of wave and the damping of sea, the period and amplitude of the swaying will tend to stabilize. The sailing vessel has six degrees of freedom, including Surge, Sway, Heave, Roll, Pitch and Yaw, as shown in Figure 1. The displacement matrix $\boldsymbol{X}(t)$ can be represented by above six parameters. In general, the motion of the vessel can be determined by the amplitude response operators (RAOs) corresponding to the above 6 degrees of freedom [19]. Each displacement RAO consists of a pair of numbers that define the vessel's response to a specific degree of freedom in a specific wave direction and period. Therefore, the displacement matrix $\boldsymbol{X}(t)$ of the vessel under the action of different waves can be obtained with the RAOs of the laying vessel.

At the same time, the radiating force of the fluid is generated by the change of the surrounding fluid due to the motion of the vessel. When calculating the radiative force, assuming that the fluid surrounding the vessel is an ideal fluid, the wave can be approximated as a linear wave. Using potential theory, the following representation can be obtained [20]:

$$\boldsymbol{f}_{rad}(t)=-\boldsymbol{A}(\infty)\ddot{\boldsymbol{X}}(t)-\int_0^t \boldsymbol{K}(t-\tau)\dot{\boldsymbol{X}}(\tau)d\tau \tag{2}$$

where $\boldsymbol{A}(\infty)$ represents the additional mass of the vessel at infinite frequency. The second term represents fluid memory, which captures the transfer of fluid energy generated by the motion of the vessel in the form of free surface radiation waves. The convolution term $\boldsymbol{K}(t)$ is a matrix of retardation or memory functions. It contains the energy dissipation caused by the radiation waves generated by the vessel's motion.

When the other loads applied to the vessel are neglected in the frequency domain, its form of motion can be defined as:

$$\left\{-\omega^2\left[\boldsymbol{M}+\boldsymbol{A}(\omega)\right]+j\omega\boldsymbol{B}(\omega)+\boldsymbol{C}\right\}\boldsymbol{X}(j\omega)=\boldsymbol{F}_{wave}(j\omega) \tag{3}$$

where $\boldsymbol{A}(\omega)$ and $\boldsymbol{B}(\omega)$ represents the frequency and additional mass of the damping matrices, respectively. $\boldsymbol{X}(j\omega)$ represents the amplitude and phase of the vessel motion, $\boldsymbol{F}_{wave}(j\omega)$ represents linear forces caused by waves. Ogilvie determined $\boldsymbol{A}(\omega)$ and $\boldsymbol{B}(\omega)$ directly by applying a Fourier transform in a sinusoidal regime:

$$\boldsymbol{A}(\omega)=\boldsymbol{A}(\infty)-\frac{1}{\omega}\int_0^\infty \boldsymbol{K}(t)\sin(\omega t)dt \tag{4}$$

$$\boldsymbol{B}(\omega)=\int_0^\infty \boldsymbol{K}(t)\cos(\omega t)dt \tag{5}$$

By Fourier transform, $\boldsymbol{K}(t)$ and $\boldsymbol{K}(j\omega)$ can be represented by $\boldsymbol{A}(\omega)$ and $\boldsymbol{B}(\omega)$:

$$\boldsymbol{K}(t)=\frac{2}{\pi}\int_0^\infty \boldsymbol{B}(\omega)\cos(\omega t)d\omega \tag{6}$$

$$\boldsymbol{K}(j\omega)=\int_0^{\infty}\boldsymbol{K}(t)e^{-j\omega t}dt=\boldsymbol{B}(\omega)+j\omega\left[\boldsymbol{A}(\omega)-\boldsymbol{A}(\infty)\right] \tag{7}$$

Therefore, the vessel's radiating force under different environmental forces can be obtained by calculating the vessel's damping matrix and additional mass matrix.

2.4. Metocean Conditions

2.4.1. Wind Conditions

Wind loads on vessels are calculated according to the formula given by the Oil Companies International Marine Forum (OCIMF) on the Prediction of Wind and Current Loads on Very Large Crude Carriers. A varying or constant wind direction and velocity can be simulated by a model with different kinds of spectra. The calculation formula for wind load is:

$$\begin{cases} X_{wind}=0.5\rho_a A_f {U_R}^2 C_{wx} \\ Y_{wind}=0.5\rho_a A_s {U_R}^2 C_{wy} \\ N_{wind}=0.5\rho_a A_s L_{BP} {U_R}^2 C_{wn} \end{cases} \tag{8}$$

where X_{wind} and Y_{wind} represent wind load in X and Y directions, respectively, N_{wind} represent wind load moment along OZ axis, ρ_a is the air density, A_f and A_s are the side projected area of vessel and the front projected area, respectively. U_R is the average wind speed, L_{BP} is the vessel vertical length, C_{wx}, C_{wy}, C_{wn} are the wind force and wind moment coefficients. They are derived from a hull model wind tunnel test conducted at the University of Michigan in 1960 [21].

$$\boldsymbol{f}_w(t)=[X_{wind} \quad Y_{wind} \quad 0 \quad 0 \quad 0 \quad N_{wind}]^T \tag{9}$$

2.4.2. Current Field

The calculation of ship flow loads is also calculated according to the formula given in Section 2.4.1. The calculation formula for current load is:

$$\begin{cases} X_c=0.5\rho_c L_{BP} D {U_c}^2 C_{cx} \\ Y_c=0.5\rho_c L_{BP} D {U_c}^2 C_{cy} \\ N_c=0.5\rho_c {L_{BP}}^2 D {U_c}^2 C_{cn} \end{cases} \tag{10}$$

where X_c and Y_c represent current load in X and Y directions, respectively, N_c represents wind load moment along OZ axis, ρ_c is the water density, D is the vessel draught, U_c is average velocity, C_{cx}, C_{cy}, C_{cn} are the current force and current moment coefficients. They can also be obtained by the spectrum in the data given by OCIMF. Therefore, the current load on the laying vessel can be expressed as

$$\boldsymbol{f}_c(t)=[X_c \quad Y_c \quad 0 \quad 0 \quad 0 \quad N_c]^T \tag{11}$$

2.4.3. Wave Conditions

In general, waves are characterized by statistics, including wave height, period and power spectrum. The spectral characterization of the wave conditions is very important in the determine the dynamic behavior of the flexible pipeline during the laying process. JONSWAP wave spectrum is usually used in engineering to calculate wave load [22], which was proposed by the United States, the Netherlands, the United Kingdom, and Germany in the "North Sea Joint Wave Project" between 1965 and 1970 [23]. The wave spectrum formula is expressed by the wave's sense height and wave peak period:

$$S_{\varsigma}(\omega)=319.34\frac{\overline{\varsigma}^{2}_{W/3}}{{T_p}^4\omega^5}\left\{-\frac{1948}{(T_p\omega)^4}\right\}3.3^{\exp\left[-\frac{(0.159\omega T_p-1)^2}{2\sigma^2}\right]} \tag{12}$$

where T_p is the peak period of the spectrum, that is, the period corresponding to the largest spectral value in the wave spectrum. σ represents the peak attitude parameter. ω represents the peak period of the spectrum.

2.5. Pipeline Model

Compared with traditional rigid pipes, the structure of flexible pipes is more complex. The flexible pipe is manufactured in a layered structure, composed of layers of materials with different structures and functions [24]. This layered structure makes the flexible pipe have a better compressive strength, corrosion resistance and other properties, but it greatly increases the computational cost during the dynamic analysis. Therefore, the flexible pipe is assumed to be a uniform, continuous, isotropic single-layer pipe, as shown in Figure 2.

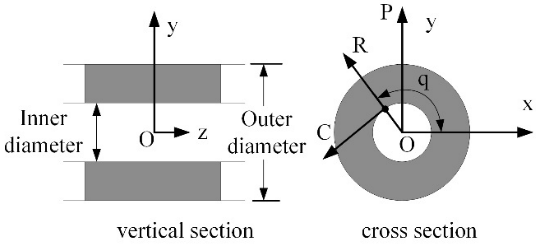


Figure 2. Simplified pipeline model.

During the process of the Flex-lay, the tension $f_p(t)$ of the pipeline at the point A is mainly composed of two parts. One part is the axial tension caused by the wet weight of the underwater pipeline, which can be obtained by the static natural catenary algorithm. The other part is the hydrodynamic load on the pipeline, which can be obtained through the semi-empirical Morison equation.

Therefore, $f_p(t)$ can be expressed as:

$$f_P(t)=\boldsymbol{F}_T+\boldsymbol{F}_{\mathrm{Morison}} \tag{13}$$

Because the catenary method ignores the effects of pipe bending and torsional stiffness, the catenary algorithm calculation results are very close to the true equilibrium [25]. Because of the characteristics of flexible pipes, the results of the catenary model are more accurate. The attitude of the pipeline located in the ocean can be expressed as the catenary state shown in Figure 3a. The coordinate origin of the model is the touch down point of the pipe, x-axis represents the horizontal direction, z-axis represents a vertical direction, α represents the angle of pipe laying, $\boldsymbol{F}_T(x)$ represents the tension of unit pipe. The basic governing equation of catenary theory is:

$$z''(x)=\delta\sqrt{1+\left[z'(x)\right]^2} \tag{14}$$

where $\delta = w/H$, w indicates the wet weight of the pipe, H represents the constant horizontal component of the tension. The tension of the unit pipeline at any position can be obtained:

$$F_T(x)=\frac{w}{\delta}ch(\delta x) \tag{15}$$

Hydrodynamic in-line forces from the current, acting on the pipeline, apply to an accelerated fluid environment in which the pipeline is kept vertical and stationary [26]. The hydrodynamic force on the pipeline can be expressed as Morison's equation as:

$$F_{morison}=0.5\rho_w C_d D\mathbf{u}\left|\mathbf{u}\right|+\rho_w C_w A\dot{\mathbf{u}}+\rho_w A\dot{\mathbf{u}} \tag{16}$$

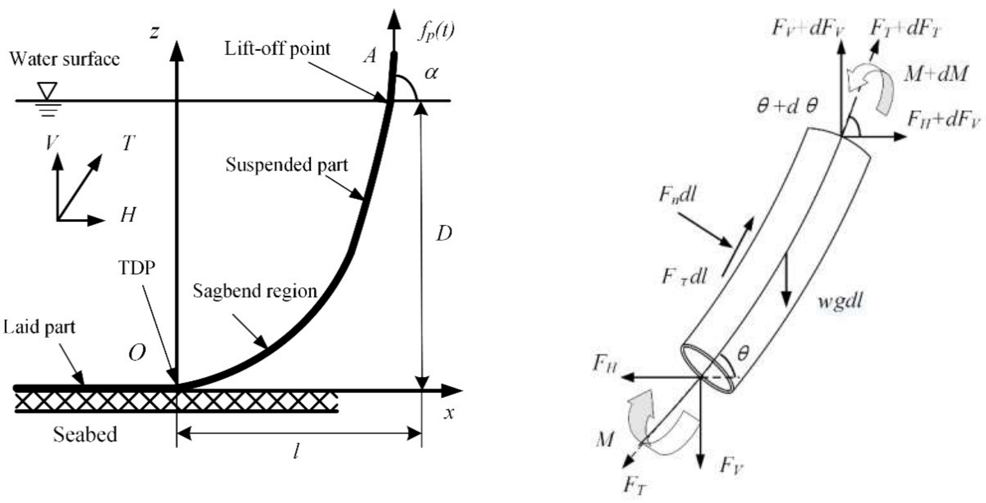
In the equation, ρ_w represents the density of water, D is the outer diameter of the pipeline, A represents the cross-sectional area of the pipe, $\mathbf{u}$ represents the velocity of the fluid, C_d and C_w

represents the drag coefficient and the hydrodynamic mass, respectively. When the ocean load acts on the unit pipeline, the above formula can be decomposed into the drag force of the unit pipeline in the ocean in the normal and tangential directions F_n and F_τ:

$$F_n = 0.5\rho_w C_n D_1 (v\sin\theta)^2 \tag{17}$$

$$F_\tau = 0.5\rho_w C_\tau D_1 (v\cos\theta)^2 \tag{18}$$

where C_n and C_τ represents the normal and tangential drag coefficients, v represents the current velocity at the position of the pipeline unit, θ is the angle between the unit pipe and the horizontal direction. Therefore, the force on any position of the pipeline can be expressed as shown in Figure 3b. Under the load of the current, the tension of the pipeline at point A can be obtained by using the iterative method.



(a)

(b)

Figure 3. Underwater pipeline model: (a) Attitude of underwater pipeline; (b) Force of pipeline unit.

3. Numerical Implementation and Dynamic Characteristic Analysis

3.1. Operating Parameters

In general, the environment of Flex-lay operations can be expressed by sea state, and sea state can be divided into nine levels according to international standards. The Flex-lay operation should be capable of performing under the conditions of fourth-level sea state, so the marine environment of pipeline dynamic analysis is set to the fourth-level sea state. In addition, the flexible pipeline will be subject to the reaction force from the seabed, which is linearly related to the depth of the pipeline sinking into the sea floor [27]. Therefore, the parameters of the marine environment are set as shown in Table 1.

Table 1. Marine environmental parameters.

Parameter	Value	Parameter	Value
Depth	3000 m	Seabed stiffness	100 kN/m/m^2
Sea density	1025 kg/m^3	Seabed damping	1.0250
Sea temperature	15 °C	Surface current velocity	1.028 m/s
Seabed current velocity	0 m/s	Kinematic viscosity	1.35×10^{-6} m^2/s
Air kinematic viscosity	15×10^{-6} m^2/s	Spectral peak period	6.1~16.2 s
Wave height	1.25–2.5 m	Air density	1.29 kg/m^3
Wave type	JONSWAP	Wind speed	8.0–10.8 m/s

HYSY201 is the first S-lay vessel for deep water in China, and mainly used for S-lay operations. It can also be used to do Flex-lay tasks after modification [28]. HYSY201 is used as the mother vessel for analysis, and the vessel parameters are shown in Table 2. The speed of the vessel is not considered in this analysis, and the default speed is 0.

Table 2. Vessel parameters.

Parameter	Value	Parameter	Value
overall length	204.65 m	Vertical spacing	185.00 m
molded breadth	39.20 m	molded depth	14.00 m
structure draft	11.00 m	operation draft	7~9.5 m
Ship displacement	59,101 T	deadweight	34,850 T
metacenter height	8.20 m	Height center	13.60 m

At present, the main pipe manufacturers in the world are Technip, Wellstream and Flexibles. Therefore, the 10-inch flexible pipe from Technip company is selected as the preset object. The performance parameters of the 10-inch flexible pipe produced by Technip company are showed in Table 3.

Table 3. Pipe parameters.

Parameter	Value	Parameter	Value
inner diameter	254 mm	Tensile stiffness	3.09×10^{8} N/m
outer diameter	352.42 mm	Bending stiffness	3.21×10^{5} N·m
Line density	4437 Kg/m^3	Young modulus	6.04×10^{6} MPa
allowable stressed	31 MPa	Poisson's ratio	0.3
Yield strength	549 MPa	Yield strength	414 MPa

3.2. Vessel Response Parameter

The hydrodynamic model of HYSY201 is established by the software AQWA, and the values of the vessel damping coefficient and additional mass are obtained by calculating the hydrodynamic model file, as shown in Figures 4 and 5. Figure 4 shows that the damping coefficient of the vessel increases first with the increase of the period, then gradually decreases after reaching the peak. Figure 5 shows that the additional mass of the vessel decreases first and increases with the increase of the period, and then decreases continuously after reaching the peak. The maximum value of the damping coefficient and the additional mass moment of the vessel in the pitch and sway is much larger than the value in the roll direction.

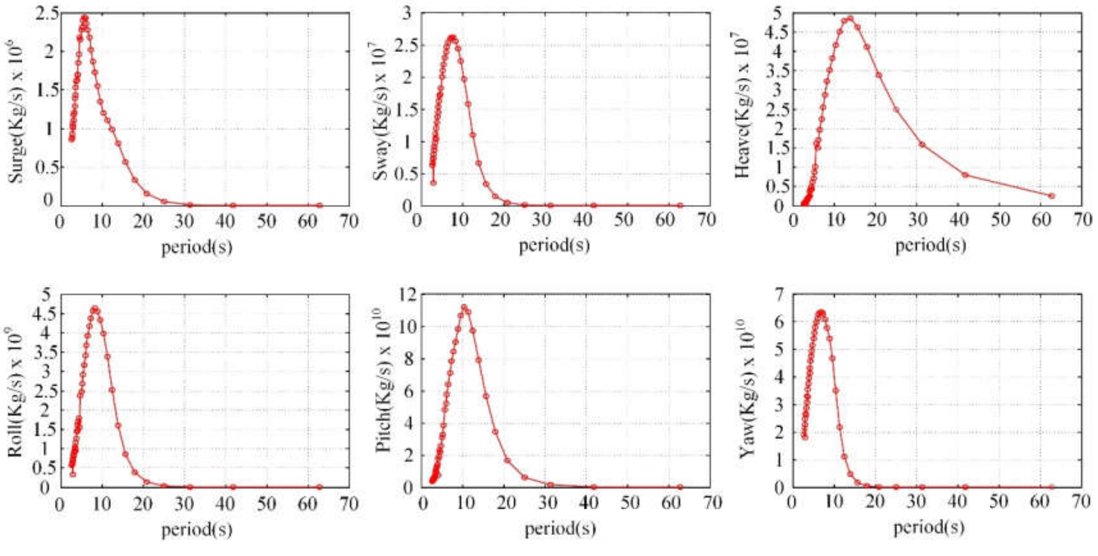


Figure 4. Vessel damping coefficient.

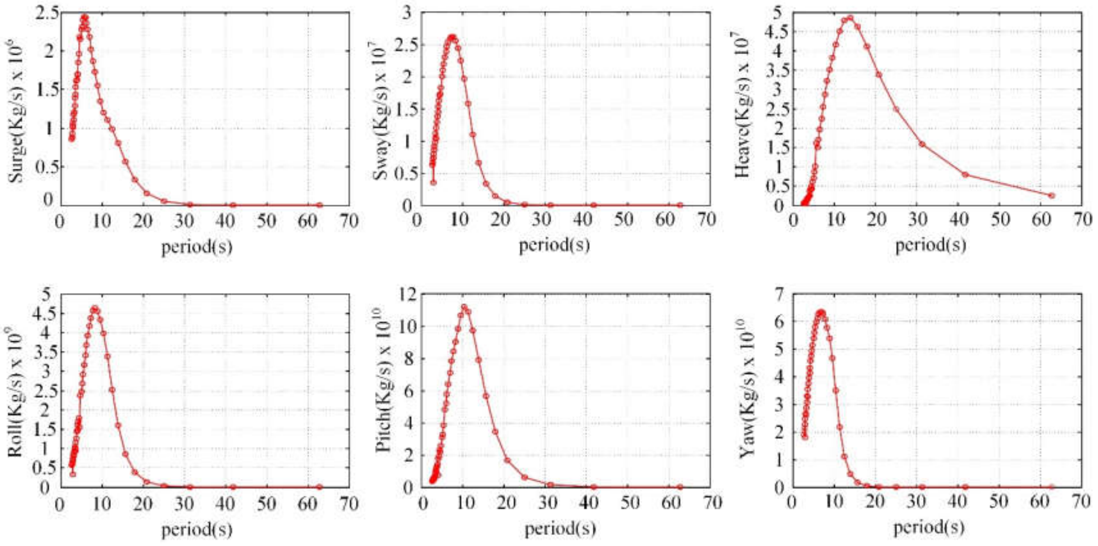


Figure 5. Vessel additional mass.

Figure 6 shows the response spectrum of vessel motion based on the displacement response amplitude operators (RAOs). It can be observed from the figure, under wave conditions, that almost all the responses of the vessel are very significant, especially the Roll motion, which is the most drastic. The vessel motion response curves coincide with 0° and 180°, 45° and 135° in the wave direction, indicating that the symmetry of the mother vessel along the section is better. The response of Pitch and Surge motion is larger at the wave direction of 0° and 180°, and the response of Heave Roll and Swage motion is larger at the wave direction of 90°.

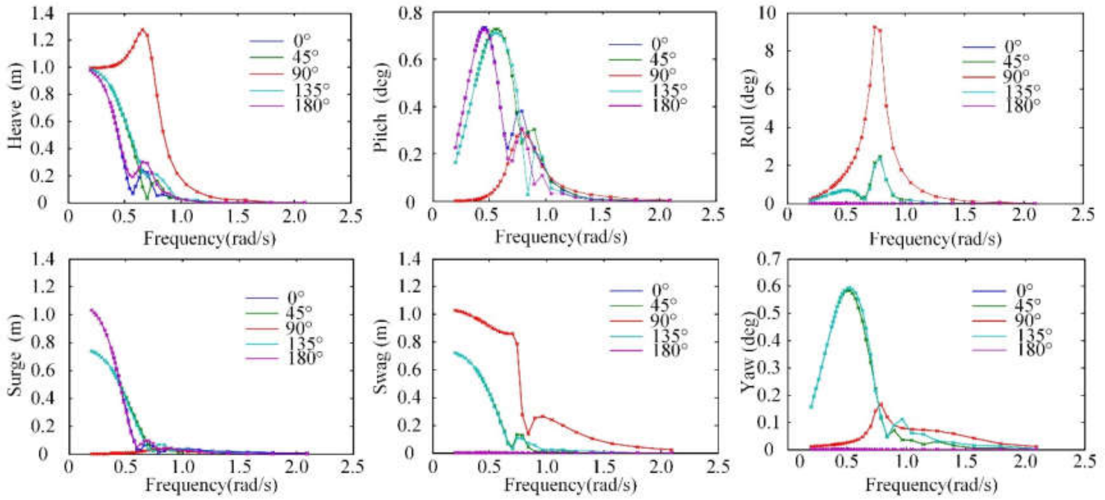


Figure 6. Vessel amplitude response operator (RAO) response.

3.3. Dynamic Simulation

The dynamic analysis begins at the static equilibrium position, which can be determined by the pipeline model described above. The initial equilibrium position of the Flex-lay system was determined through calculation, and the starting configuration was provided for dynamic simulation. Subsequently, by considering the effects of marine loads and vessel motion, a model of the Flex-lay system that fully considers various complex non-linear problems is established. The model is composed of three parts: marine environment, flexible pipeline and laying vessel. Finally, the appropriate time step was selected through a large number of experimental analyses, and the axial tension, bending moment, stress and strain of the pipeline were calculated at each time step to study the dynamic behavior of the pipeline during the process of Flex-lay.

Under the above conditions, a numerical simulation is performed on the laying process of the Flex-lay. The time history of the pipeline top tension is shown in Figure 7. The maximum dynamic tension of pipeline is 4627 kN at 145 s, which is 42.7% higher than the static tension of 3242 kN, and the minimum dynamic tension of the pipeline is 1823 kN, which is 43.7% lower than the static tension. It can be seen that during the laying of flexible pipelines, the impact on the pipeline under the interaction of marine loads and vessel motion is very significant. Therefore, the design of the Flex-lay system needs to consider the pipeline dynamic tension.

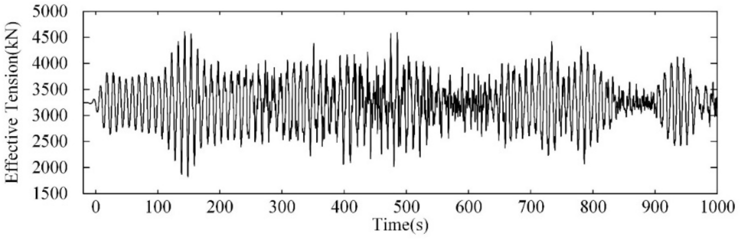
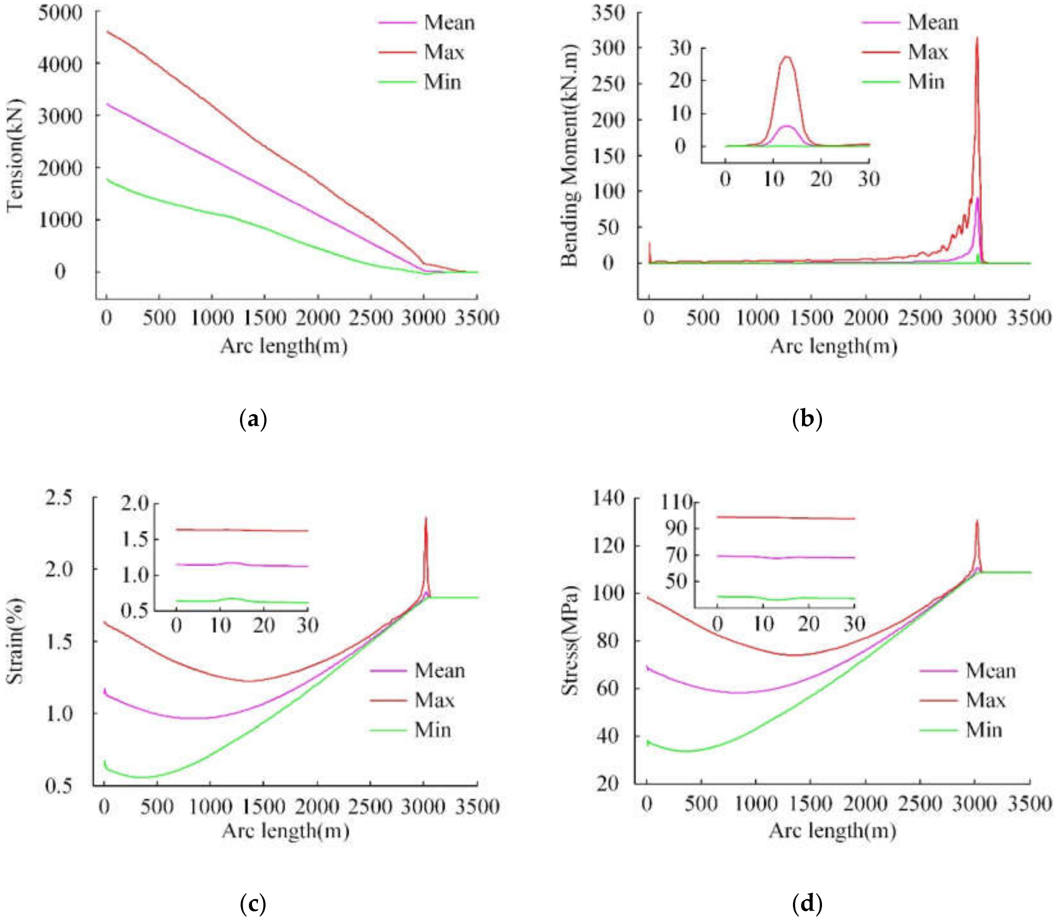


Figure 7. Time histories for the flexible pipeline top tension.

Figure 8 shows the maximum and minimum values of axial tension, bending moment and stress and strain of the pipeline during the period of 0–200 s. As shown from Figure 8a, there is a significant difference between the static axial tension and the maximum and minimum axial tension of the pipeline. The largest gap between the maximum and minimum tension of the pipeline appears at the separation position between the pipeline and the tensioner, as the length of the pipeline increases, the difference between the maximum and minimum axial tension gradually decreases until the maximum, minimum and equivalent values coincide at the touchdown point.

From Figure 8b, it can be seen that the bending moment of the pipe, the static and the maximum and minimum bending moments of the pipe show a small fluctuation, which occurs near the separation point between the pipeline and the tensioner. After this, it approaches zero and no obvious changes are observed in the suspended part. However, as the pipeline enters the sag bend region, the bending moment of pipe shows obvious differences, and reaches a maximum value of 314 kN.m near TDP (Touch Down Point), which is 220% higher than the static maximum bending moment of 93.41 kN.m. In addition, it can be observed that there are obvious fluctuations in the curve, which indicate that the submarine pipeline will produce a large disturbance during the laying process.

It can be seen from Figure 8c,d that the stress and strain of the pipeline have a good correlation. Similar to the bending moment of the pipeline, the maximum stress–strain value of the pipeline appears near TDP. However, the difference is that the dynamic change of the stress and strain of the pipe has a very obvious change at the maximum and minimum values at the point of separation from the tensioner, and then gradually decreases until a significant change appeared near the point of TDP again. The maximum strain value is 2.354% and the maximum stress value is 130.7 Mpa, which are 52% and 18.7% larger than the static value, respectively. In summary, the results show that the marine environment and the motion of vessel have a significant impact on the dynamic behavior of the pipeline.



(**a**) (**b**)

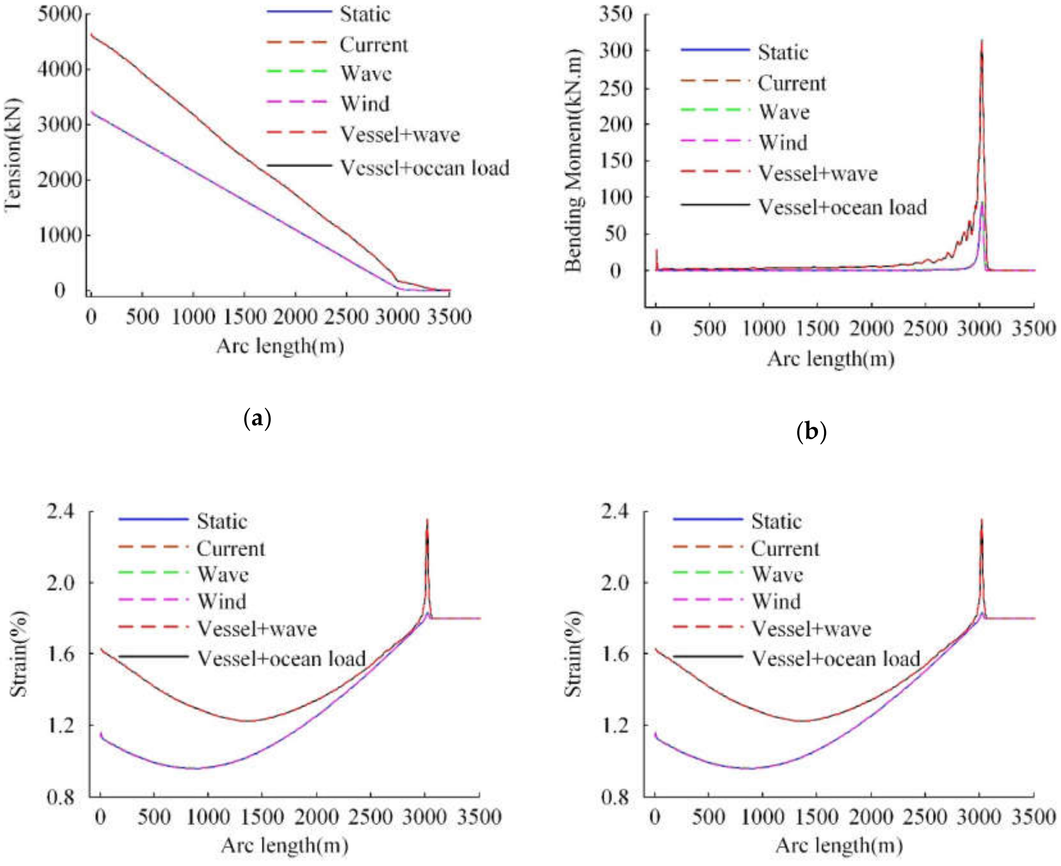
(**c**) (**d**)

Figure 8. Dynamics behavior of the pipeline: (**a**) Axial tension; (**b**) Bending moment; (**c**) Strain; (**d**) Stress.

4. Influencing Factors of Dynamic Behavior

4.1. Influence of Different Factors

According to the above results, it can be deduced that the dynamic behavior of the pipeline will change due to the effects of marine loads and vessel motions. In order to determine the influence of marine loads and vessel motion on the dynamic behavior of the pipeline during the Flex-lay, three cases were studied: wind load, current load and wave load acting independently; wave load and vessel interaction and all factors acting together. The value of the maximum axial tension, bending moment and stress–strain of the pipeline along the length is shown in Figure 9. It can be seen from the figure that compared with the results of static analysis that in the absence of vessel interaction, the effects of wind load and current on the pipeline are not obvious, and wave loads have a slight impact on the dynamic behavior of the pipeline. When the vessel interaction is taken into account, the dynamic response of the pipeline becomes very obvious, which shows the importance of the interaction between the marine loads and the vessel's motion on the dynamic behavior of the pipeline. However, the dynamic response of the vessel is fixed when the laying vessel is selected, since the influence of waves on the dynamic behavior of the flexible pipeline during the Flex-lay operation is studied in the following analysis.



(**a**) (**b**)

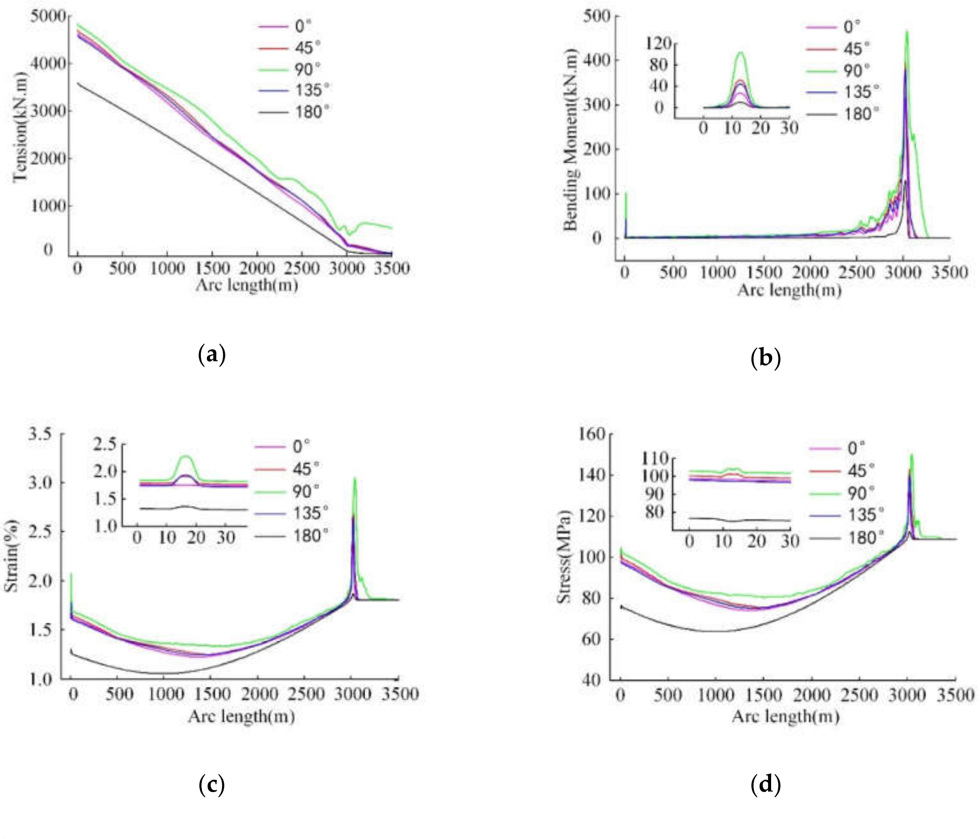
(**c**) (**d**)

Figure 9. Effect of different factors on pipeline dynamic responses: (**a**) Axial tension; (**b**) Bending moment; (**c**) Strain; (**d**) Stress.

4.2. Influence of Wave Direction

In order to illustrate the impact of wave direction on the pipeline dynamic behavior during the Flex-lay operation, the wave state is specified with a significant wave height of 2.5 m and a peak period of eight seconds, and the wave direction is 0°, 45°, 90°, 135° and 180°, respectively. Under the above conditions, the dynamic behavior of the flexible pipeline was analyzed by using OrcaFlex software, and the axial tension, bending moment and stress and strain of the pipeline were obtained. The results are shown in Figure 10, which shows that under different wave directions, there are obvious differences in axial tension, bending moment and stress–strain of the flexible pipeline.

Figure 10a shows clearly that the axial tension of the pipeline dramatically varies with different wave direction. Under 90° wave conditions, the maximum axial tension at the position where the pipe leaves the tensioner is 4826 kN, but the maximum axial tension at the same position is 3594 kN under 180° wave conditions, and the difference between the two conditions is 34.3%. Similarly, Figure 10b shows the maximum bending moments near the TDP were 465.6 kN.m and 130.1 kN.m, respectively, the difference reached 257%. It can be seen from the figure that the response curve is very smooth under the 180° wave condition, but the curve will fluctuate under the other wave directions, especially under the 90° wave direction. Figure 10c,d show that the maximum von-Mises stress of pipelines under the 90° wave and 180° wave is 157 MPa and 113 MPa, respectively, with a difference of 38.9%, and the corresponding maximum strain is 3.05% and 1.87%, respectively, with a difference of 63.1%. In addition, it can be seen from the Figure 10b–d that under the 90° wave conditions, the maximum values of the bending moment, stress, and strain of the pipeline will shift to the right, and the pipelines of laid part will generate a response. In summary, the simulation results fully show that the wave direction has a very significant effect on the pipeline dynamic response, of which the 90° wave direction has the greatest impact on the pipeline, and the 180° wave direction is the most favorable for pipeline laying.



(a)

(b)

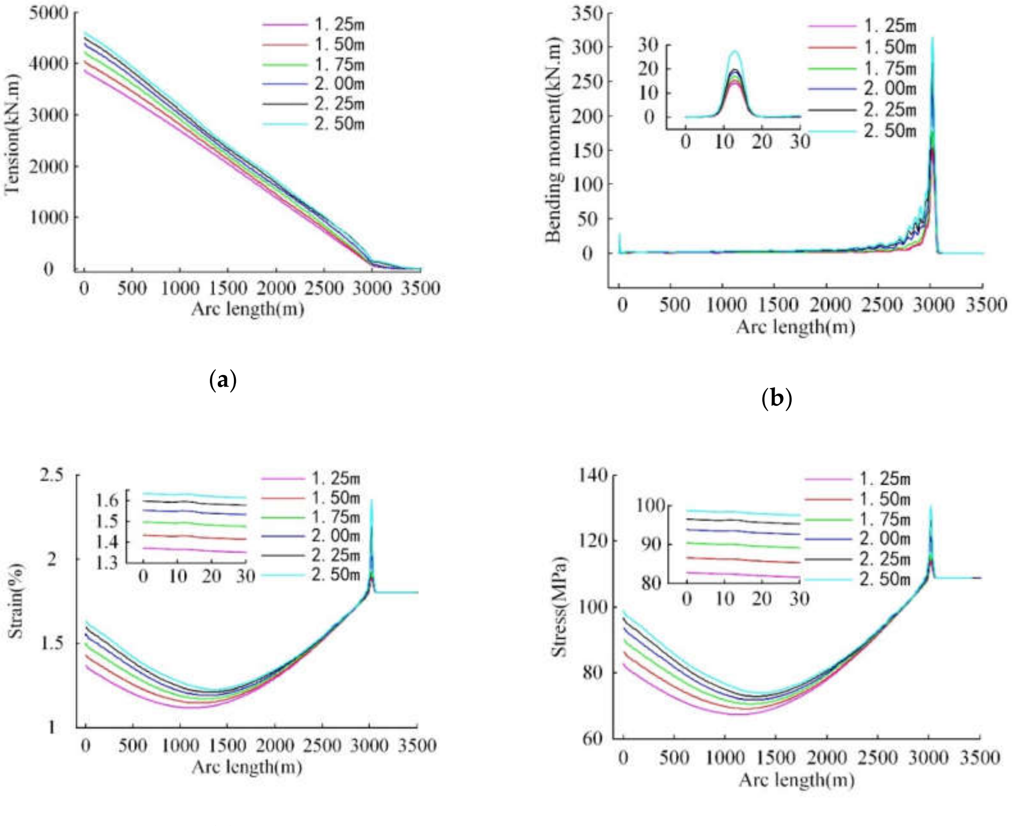
(c)

(d)

Figure 10. Effect of wave heading on pipeline dynamic responses: (**a**) Axial tension; (**b**) Bending moment; (**c**) Strain; (**d**) Stress.

4.3. Influence of Wave Height

Wave height is considered to be another important factor in the dynamic behavior of the pipeline. In order to investigate the effect of wave height on the pipeline during the Flex-lay operation, the wave conditions with a wave direction of 0° and a peak period of eight seconds is selected to simulate the dynamic behavior of pipeline under different wave heights of 1.25 m, 1.50 m, 1.75 m, 2.00 m, 2.25 m and 2.50 m respectively. Figure 11 shows the axial tension, bending moment, stress and strain of the pipeline under the above conditions, and the results show that the dynamic response of the pipeline is significantly different at varied wave heights. Figure 11a,b shows that the maximum axial tension and bending moment of the pipeline are 4624 kN and 314.2 kN.m for Hs=2.5 m, and the maximum axial tension and bending moment of the pipeline are 3883 kN and 145 kN.m for Hs=1.25 m. The differences under the two wave states are 19.1% and 116.7%, respectively. Figure 11c,d show the maximum stress of the pipeline under the 2.5 m and 1.25 m waves conditions is 130.7 MPa and 113.5 MPa, respectively, with a difference of 15.2%, and the corresponding maximum strains are 2.35% and 1.88%, the difference is 25%. It can be observed from the Figure 11 that the response of the pipeline increases as the wave height increases, and the trend of the response curve of the pipeline is almost identical. When the wave height is less than 2 m, the dynamic response of pipeline is not obvious. However, when the wave height is more than 2 m, the response of the pipeline becomes significant. Therefore, it should be avoided during the Flex-lay operation when the wave height is higher than 2 m.



(a)

(b)

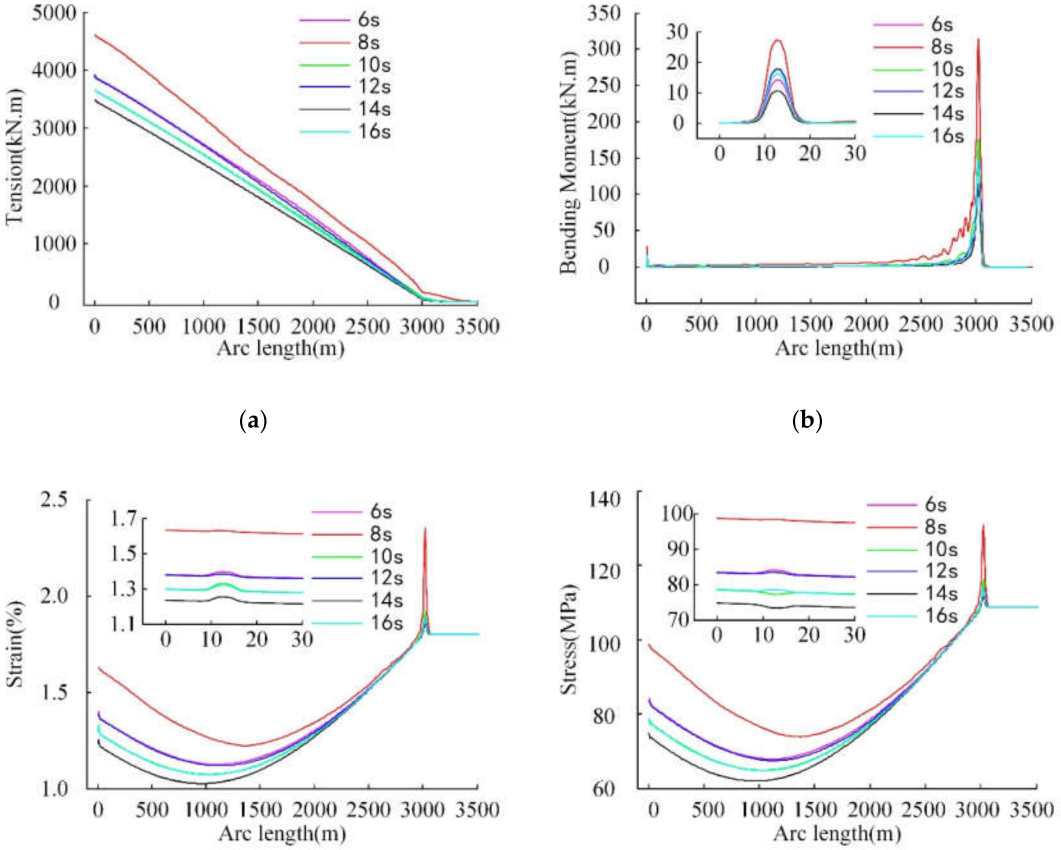
(c)

(d)

Figure 11. Effect of wave height on pipeline dynamic responses: (**a**) Axial tension; (**b**) Bending moment; (**c**) Strain; (**d**) Stress.

4.4. Influence of Spectral Peak Period

As a very important parameter of wave load, the spectral peak period has a significant impact on the dynamic response of the pipeline during the Flex-lay operation. Under the sea conditions described above, six periods are selected in the range of 6 s to 16 s for analysis. The dynamic response of the pipeline is obtained, shown in Figure 12. Figure 12a shows the maximum axial tension of the pipeline under different spectral peak periods. At the disengagement position of the pipeline from the tensioner, the maximum value is 4627 kN in the 8.0 s spectral peak period and the minimum value is 3502 kN in the 14 s spectral peak period. The difference between the two wave conditions is 32.1%. Similarly, it can be seen from Figure 12b, under the two spectral peak periods, the maximum bending moments near the bottoming point were 314.2 kN.m and 114.7 kN.m, respectively, with a difference of 173.9%. Figure 12c,d reflects the maximum stress and strain values of the pipeline under the above two wave conditions, respectively 130.7 MPa and 111.7 MPa, 2.35% and 1.85%, the corresponding differences are 17% and 27%. The simulation results show the impact of the wave spectrum peak period on the dynamic response of the pipeline, it has the greatest impact on the pipeline under the spectrum peak period of eight seconds. In addition, for the 10 second and 16 second case, the effect of the waves of the spectral peak period on the dynamic response of the pipeline is almost the same.



(**a**) (**b**)

(**c**) (**d**)

Figure 12. Effect of peak spectral period on pipeline dynamic responses: (**a**) Axial tension; (**b**) Bending moment; (**c**) Strain; (**d**) Stress.

5. Conclusions

In this paper, a dynamic coupling model for deepwater Flex-lay, considering the laying vessel motion, marine state and pipeline dynamics model, was established to study the dynamic behavior of flexible pipelines during the pipe laying process. Based on the above model, the marine environment of the four-level sea condition was analyzed. The natural catenary theory and Morison's equation were both used to determine the initial attitude of the flexible pipeline during the laying process. The hydrodynamic analysis of the pipelaying vessel HYSY201 was carried out by using the finite element software AQWA. The comprehensive finite element model of deepwater flex-lay system was established by using OrcaFlex, and used to carry out an illustrative example analysis of a 10-inch flexible pipeline being laid onto the seabed with a water depth of 3000 m. The flexible pipeline dynamic behavior including axial tension, bending moment and stress–strain in the laying process were studied. The results show a significant correlation between the marine loads and the dynamic response of the pipeline. The following conclusions were obtained:

(1) The dynamic response of the axial tension is the largest at the position where the pipeline is released from the tensioner and gradually decreases with the increase of the water depth, the maximum tension of the pipeline increases by 42.7% compared with the static tension. The bending moment of the pipeline is almost zero at suspended part and changes drastically enters the sag bend region. The maximum bending moment of the pipeline is increased by 220% compared with the static bending moment. There is a good correlation between the stress and strain of the pipeline. The maximum stress and strain values of the pipeline appear near TDP. The maximum value of the strain and the maximum stress value are 52% and 18.7% larger than the static values, respectively. It is proven that the marine loads and vessel motion have a significant effect on the dynamic response of the pipeline.

(2) In the absence of vessel interaction, the effect of the wind and the current on the dynamic behavior of the pipeline is not obvious, and the wave load has a slight impact on the dynamic behavior of the pipeline. However, adding to the interaction of the vessel, the dynamic behavior of the pipeline becomes very obvious, which indicates that the interaction between the marine loads and the vessel motion has the most significant effect on the dynamic behavior of the pipeline.

(3) The wave direction has a great influence on the dynamic response of the pipeline. The most adverse wave direction appears at 90°, which has the greatest impact on the pipeline response. The most favorable wave direction is 180°, which has the least impact on the pipeline. The differences in axial tension, bending moment and stress–strain under the two conditions are 34.3%, 257%, 38.9%, and 63.1%, respectively. Therefore, reasonable selection of the vessel's forward direction during the Flex-lay can effectively reduce the pipeline's dynamic response.

(4) Wave height and spectral peak period are also important factors affecting the dynamic response of the pipeline. The dynamic response of the pipeline is positively related to the wave height. When the wave height is less than 2 m, the influence of the sense wave height on the dynamic response of the pipeline is small, but the influence becomes more obvious when the wave height exceeds 2 m. When the peak period of the spectrum is eight seconds, it has the greatest impact on the dynamic response of the pipeline. Therefore, the operation of the Flex-lay should be performed under the height of less than 2 m and avoid operating under the eight-second peak wave period.

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