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NUMERICAL ANALYSIS OF DEEP-WATER PIPELINE ABANDONMENT AND RECOVERY

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Key words: abandonment and recovery, deep-water, cable-pipeline system, A&R strategy.

ABSTRACT

Pipeline abandonment and recovery (A&R) is of great importance in offshore pipeline installation. A mathematical model of the A&R process is proposed based on the large deflection beam theory. To solve the model, an iteration process is adopted. The initial guess of the solution is obtained through the two-catenary approach, which significantly accelerates the iteration. A moving boundary technique is used to solve the governing equation of the suspended pipeline. With the proposed approach, the effects of the dominant parameters in the A&R process are studied. The cable length increases, and the maximum bending moment decreases, as the vessel moves forward when maintaining the top tension. The vessel slightly moves forward and the maximum bending moment decreases with the top tension when maintaining the cable length. The top tension decreases and the maximum bending moment increases as the cable length increases, when the vessel stays static. The maximum bending moment dramatically decreases when the pull-head approaches the seabed at all events. In all the cases, the proposed model shows great advantages over the simplified two-catenary method which tends to overestimate the pipeline bending moment. Three different A&R strategies are compared. The third A&R strategy that repeats the process of static vessel - constant tension can effectively control the maximum bending moment within the designed range. The proposed approach of the A&R analysis and studies conducted should be a valuable foundation for future A&R procedure design.

I. INTRODUCTION

Pipeline installation is one of the hardest engineering challenges in many deep-water oil and gas exploitations. For instance, when severe weather conditions or damages to the pipe-laying vessel are encountered during pipeline laying, the pipeline should be lowered down to the seabed by cables, then recovered once the situation has been settled. The process is called abandonment and recovery (A&R). To guarantee the pipeline integrity during the A&R process, the deformation and stress of the pipeline-cable system and the tension applied by the A&R winch should be carefully analyzed and monitored.

However, there have been few studies on analyzing pipeline A&R operations. Firstly, Andreuzzi and Maier (1981) proposed a two-catenary approach, which is a simple and efficient method for approximate static analysis, with which diagrams of the relationships between some dimensionless parameters were constructed. Datta (1982) analyzed the pipe and cable with the finite difference method and the line integration method respectively. After many years, Zeng et al. (2014) proposed a method to solve the moving boundary problem in A&R analysis. Wang et al. (2015) proposed an analytical model for the A&R operations of deep-water steel lazy-wave riser (SLWR) and then, he studied the influences on the static response of SLWR by different A&R methods. Most recently, Han et al. (2017) studied the effects of cable length, water depth and vessel-TDP distance on the pipeline response, by analyzing both the cable with catenary theory and the pipeline with numerical iteration.

The studies on pipeline abandonment and recovery are limited, while there have been quite many researches on riser responses and regular pipe-laying process. It is believed that those are of important enlightenment and reference significance to the analysis of pipeline A&R process. Chucheepsakul et al. (2003) proposed a mathematical model of extensible pipes in the Cartesian coordinates and natural coordinates, in which the effects of currents and inner flows are taken into account. Chatjigeorgiou et al. (2008, 2010a, 2010b) and Katifeoglou and Chatjigeorgiou (2012) proposed a three-dimension nonlinear dynamic model of submerged extensible catenary pipes conveying fluid and subjected to end-imposed excitations, furthermore, they also studied the dynamic interaction of catenary risers with the seafloor. Lenci and Callegari (2005) proposed a group of simplified models for J-lay analysis and studied the influence of soil rigidity on the Steel Catenary Riser (SCR) response. Kang et al. (2015) analyzed the J lay of SCR based on the catenary and large deflection beam

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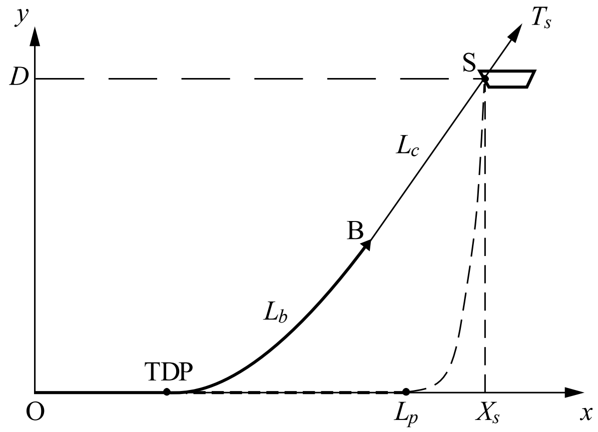

Fig.1 Schematic diagram of the pipeline abandonment problem.

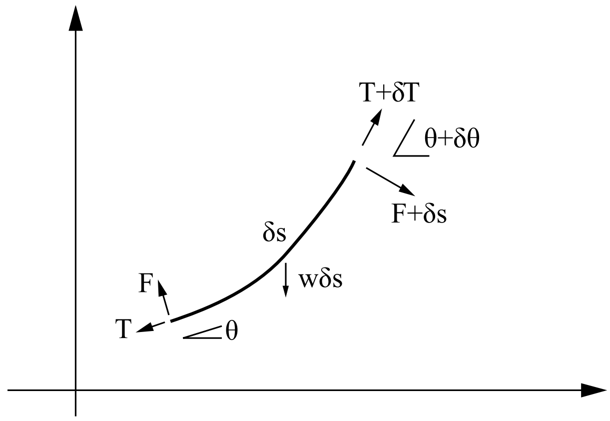

Fig. 2 Force analysis of an elastic large deflection beam element.

theory. Szczotka (2011) proposed a modification of the stiffness coefficients and the corresponding model J-lay analysis. Gong et al. (2009, 2011) made a parameter sensitivity analysis of S-lay based on the stiffened catenary theory. Duan et al. (2011) proposed an installation system for deep-water riser S-laying and carried some laboratory scale pipeline lifting experiments. Yuan et al. (2012) presented a novel numerical model for the pipeline S-lay problem. Wang et al. (2010a; 2010b; 2011) did some analyzes on both S-lay and J-lay problem, in which the ocean currents and seabed stiffness are taken into account.

In most of above studies, the cable in the A&R system is either neglected or just considered as simple catenary, which can not reflect the complex response of the cable. In the present study, an analysis model of the A&R process is proposed based on the large deflection beam theory, in which the bending rigidity of cable is considered zero. The model is solved with the fourth-order finite difference method in an iteration process. With the proposed model, the effects of cable length, top tension, and vessel position are studied. Additionally, some A&R strategies are evaluated and compared. The proposed model should provide guidance for A&R operations in offshore pipe-laying.

II. MATHEMATICAL MODEL

1. Problem Description

Pipeline A&R operations are conducted by lowering or lifting the pipeline utilizing pipe-laying vessels. These two operations are the reverse of each other. Therefore, the analysis of either one should be applicable to the other.

In this paper, only the abandonment process is studied, in which the pipeline head is first transferred from the pipe-laying apparatus, such as a stinger, to the A&R winch. Then, the cable is gradually released, and the vessel moves forward to lower the pipeline. In the process, there are three dominant parameters that determine the status, listed as follows: the cable length L_c, the top tension T_s, and the vessel position X_s which is defined here by the horizontal distance of the vessel (point S shown in Fig. 1) from the pipeline end (point O). If any two of them are known, the other one can be determined, as well as other parameters, such as the suspended pipeline length L_b and the touchdown point (TDP) position.

2. Mathematical Model of Pipelines and Cables

The cable-pipeline system can be discretized as finite elastic large deflection beam elements. For each element, the force analysis is shown in Fig. 2. The equations of force balance along and tangential to the pipe axis are,

$$F + (T + \delta T)\cdot sin\delta\theta - (F + \delta F)\cdot cos\delta\theta - w\cdot\delta s\cdot cos\theta = 0 \tag{1}$$

$$(F + \delta F)\cdot sin\delta\theta + (T + \delta T)\cdot cos\delta\theta - T - w\cdot\delta s\cdot sin\theta = 0 \tag{2}$$

According to the beam theory, the moment M and shear force F can be expressed as

$$M = EI\frac{1}{R} = EI\frac{d\theta}{ds} \tag{3}$$

$$F = \frac{dM}{ds} = \frac{d^2\theta}{ds^2} \tag{4}$$

in which R is the curvature radius.

By substituting Eqn. (3 - 4) into Eqn. (1 - 2) and eliminating the high-order components, the governing differential equations for pipelines can be derived as,

$$EI\cdot\frac{d^3\theta}{ds^3} - T\cdot\frac{d\theta}{ds} + w_b\cdot\cos\theta = 0 \tag{5}$$

$$\frac{dT}{ds} + EI\frac{d^2\theta}{ds^2}\cdot\frac{d\theta}{ds} = w_b\cdot sin\theta \tag{6}$$

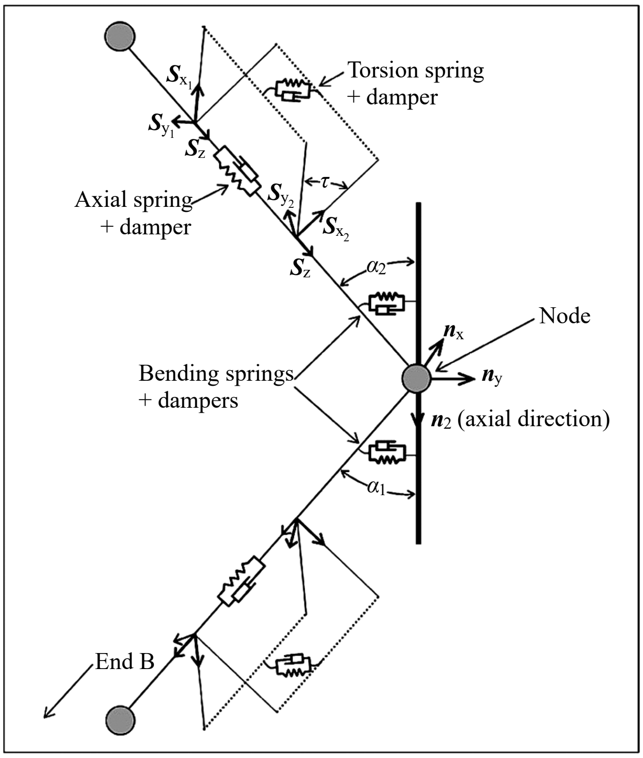

Fig. 3 Schematic diagram of the lumped mass method in Orcaflex.

in which T is the axial tension of the pipeline, w_b is the submerged weight of the pipeline, EI is the bending rigidity of the pipeline, s is the pipeline length, and θ is the deflection angle.

Similarly, the cable can be analyzed by Eqn. (5) and (6), though there is a difference. Because the cable normally has very small bending rigidity, gernerally, ignoring the bending rigidity has little impact on the result. Therefore, the governing equations for the cable can be written as

$$T \cdot \frac{d\theta}{ds} + w_c \cdot cos\theta = 0 \tag{7}$$

$$\frac{dT}{ds} = w_c \cdot sin\theta \tag{8}$$

3. Boundary Conditions

To solve the governing equations of the pipeline-cable system, the boundary conditions at different positions should be specified. For A&R operations, the bending moment and the deflection angle at the TDP should be zero. The bending moment should also be zero at the sea surface point, which actually is the A&R winch, but simplified. At the pull-head position, the cable and pipeline should be consistent in not only the displacement and angle but also the force and bending moment. Furthermore, because the heave compensation system is usually used for the A&R process (Li et al., 2018), the ship at point S is considered stationary. Mathematically, the boundary condition at the TDP point, the pull-head position (Point B in Fig. 1), and the sea surface (Point S in Fig. 1) are defined as follows:

TDP：

$$\begin{aligned} &\theta_0 = 0 \\ &M_0 = EI\frac{d\theta_0}{ds} = 0 \\ &x_0 = L_p - b \\ &y_0 = 0 \end{aligned} \tag{9}$$

Point B：

$$\begin{aligned} &\theta_{B-} = \theta_{B+} \\ &M_{B-} = M_{B+} = 0 \\ &T_{B-} = T_{B+} \\ &x_{b-} = x_{b-} \\ &y_{b-} = y_{b+} \end{aligned} \tag{10}$$

Point S：

$$\begin{aligned} &M_s = 0 \\ &T_s = T_0 \\ &x_s = \mathrm{x} \\ &y_s = \mathrm{D} \end{aligned} \tag{11}$$

4. Numerical Algorithm

As aforementioned, the condition of the pipeline-cable system can be determined if any two of the three parameters (X_s, L_c, and T) are given. As shown in Eqn. (10), the geometry and the force at the pull-head should be consistent. To solve the pipeline-cable system, an iteration process should be conducted. In the case that L_b and X_s are given, the iteration process is as follows:

a) Solve the pipeline-cable system using the two-catenary method proposed by Andreuzzi and Maier (1981), obtaining the angle and tension at the pull-head. Set them as the initial guess of the boundary conditions at the pull-head;
b) Based on the boundary conditions set in step a), solve Eqn. (5 - 8);
c) Compare the coordinates of the pipeline head and the cable head at Point B. If the calculated distance between the pipeline head and cable head is larger than the criteria, adjust the angle and tension at the pull-head;
d) Keep iterating steps b) and c) until the calculated distance between the pipeline head and cable head converges.

The governing equation Eqn. (5) for the pipeline is defined on the local coordinate system of the pipeline. However, the TDP is unknown before the problem is solved; that is, the suspended pipeline length is unknown. Therefore, a moving boundary is embedded in the mathematical model. To tackle

Table 1. Physical property parameters of the pipeline-cable system studied.

Parameters	Symbol	Value
Water depth (m)	h	1500
Submerged weight of the cable (N/m)	w_c	443.94
Submerged weight of the pipeline (N/m)	w_b	1333.64
Laid pipeline length (m)	L_p	3500
Pipeline bending rigidity ($\mathrm{N \cdot m^2}$)	EI	4.8×10^8

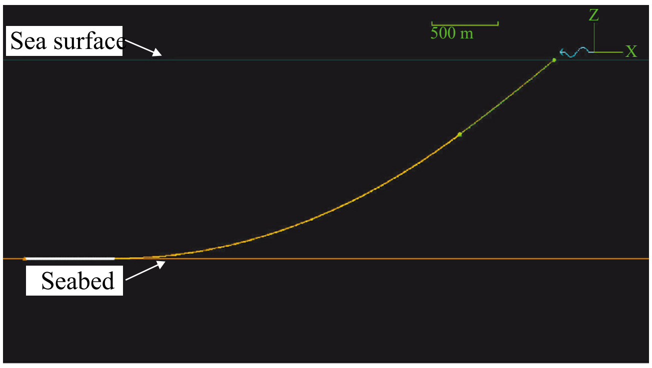

Fig. 4 Pipeline abandonment model in Orcaflex.

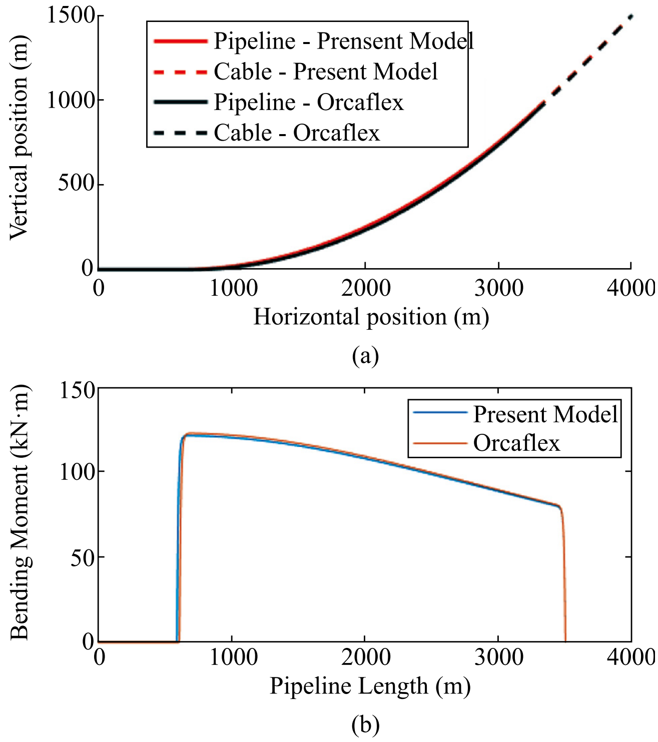

Fig. 5 Comparison between the proposed model and Orcaflex.

the moving boundary at the TDP, the moving boundary technique proposed by Zeng et al. (2014) is employed, with which the TDP position and the suspended pipeline length L_b can be determined if the tension and its angle acting on the pull-head are given. Generally, the moving boundary technique is implemented as follows:

a) Assume the tension at the TDP is $H_0 = T_0\cos\theta_0$, and the suspended pipeline length is $L_b = T_0\sin\theta_0/w_b$;
b) Solve the governing equations of the pipeline to obtain the tension T_n and its angle θ_n at the pull-head;
c) Compare T_n with $T_0\cos(\theta_n - \theta_0)$. If T_n is larger than $T_0\cos(\theta_n - \theta_0)$, reduce L_b. Otherwise, increase L_b;
d) Keep iterating the first two steps until $T_n = T_0\cos(\theta_n - \theta_0)$.

5. Model Validation

To validate the proposed model, it is compared to the widely recognized commercial software Orcaflex with a pipeline abandonment problem.

As shown in Fig. 3, the pipeline and cable are discretized as a series of line segments in Orcaflex, based on the lumped mass method. The segments model the axial, bending and torsional properties of the pipeline and cable with a series of spring-damper, while the other properties (weight, buoyance, drag force, *etc.*) are all lump ed to the nodes. The lumped mass method implemented in Orcaflex is classical, and the detailed mathematical model can be found in the official User Manual of Orcaflex (Orcina Ltd., 2019).

The Orcaflex model of pipeline abandonment is shown in Fig. 4. The pipeline and cable are modeled respectively. The top end of the cable is fixed at the sea surface, while no hydrodynamic movement of the pipelaying vessel is considered in the present study. The bottom end of the cable is connected to the top end of the pipeline with zero connection stiffness. The bottom end of the pipeline is fixed to the seabed; the seabed is assumed to be rigid; and the seabed friction is not considered here.

The validation case is configured as L_p = 3500 m, L_c= 900 m, X_s= 4000 m and h = 400 m. For the following comparison as well as for later simulations, a typical deep-water pipeline abandonment configuration is used, of which the physical properties are listed in Table 1. As shown in Fig. 5, the profile and bending moment calculated with the proposed model show little difference from those calculated using Orcaflex. The maximum bending moments are 123.68 kN · m and 127.34 kN · m respectively, with a difference of about 2.87%, which is thought to be acceptable. The difference is probably attributable to the fact that the pipeline and cable in Orcaflex are extensible, whereas their extension in the present model is neglected.

It should be noted that the present model shows advantages over the model in the work of Zeng et al.(2014), as the effect of shear force $\frac{d^2\theta}{ds^2}$ is taken into account (see Eqn. (6)). Although it nonlinearizes the equation and makes it more difficult to solve, it can improve the accuracy of the model. In Fig. 4, the present model is compared to that of Zeng et al. (2014).

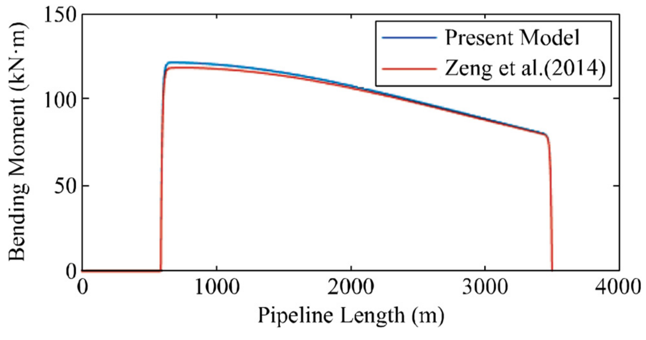

Fig.6 Comparison of the bending moment between the proposed model and Zeng et al.(2014).

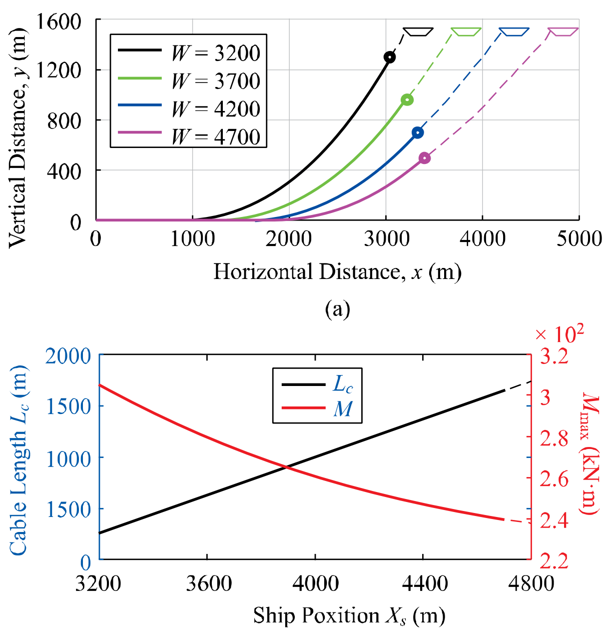

Fig. 7 Analysis results of pipeline abandonment under constant top tension.

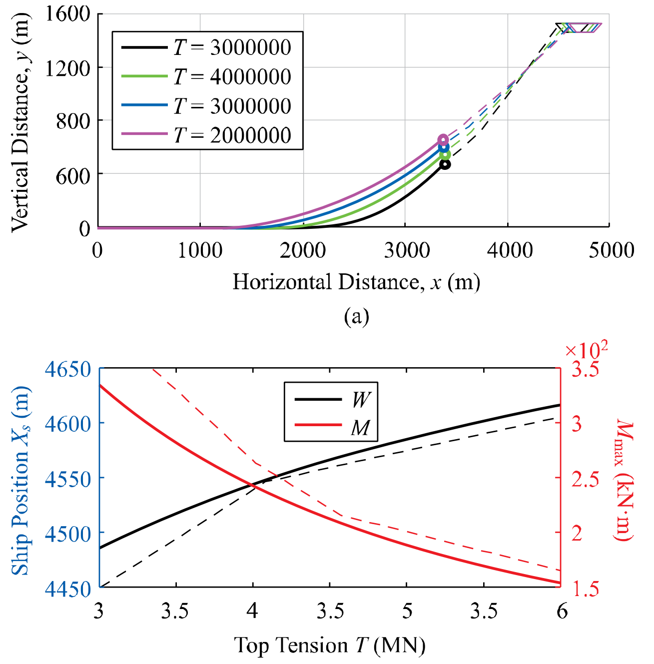

Fig. 8 Analysis results of pipeline abandonment under constant cable length.

Although there is little difference between the suspended pipeline profiles, the bending moments in the pipelines show a significant difference of about 4.52% at the TDP, as shown in Fig. 6.

III. PARAMETRIC STUDY

Because the three dominant parameters can be easily monitored in the A&R process, their effects are studied in this section. Along with the interaction between themselves, their influence on the bending moment in the pipeline is studied. The physical property parameters of the pipeline-cable system are summarized in Table 1.

1. Effects of Vessel Position

To study the effects of vessel position on pipeline abandonment, four different vessel positions are considered, and the other parameters remain the same. In these cases, the vessel-to-pipeline end distance X_s increases from 3200 m to 4700 m by 500 m per case, while the top tension is maintained at T_s = 4.4 MN. The numerical results are obtained using the proposed algorithm.

The cable-pipeline profiles for different vessel positions are plotted in Fig. 7a. It shows that the cable length increases as the vessel moves forward, while the pipeline pull-head is lowered. Fig 7b shows the effects of the vessel position on the cable length and the maximum pipeline bending moment. Under constant top tension, the maximum bending moment decreases and the cable length increases as the vessel moves away. The effects of vessel position are also analyzed using the simplified method proposed by Andreuzzi and Maier (1981). These effects are plotted in Fig. 5b with the dashed line. It is shown that the simplified method and the present method show little difference in this case.

2. Effects of Top Tension

To analyze the top tension effects, a series of simulations are conducted with the cable length maintained at L_c=1500 m. In these simulations, the top tension increases from 3 MN to 6 MN by 1 MN per case, and the vessel position changes correspondingly.

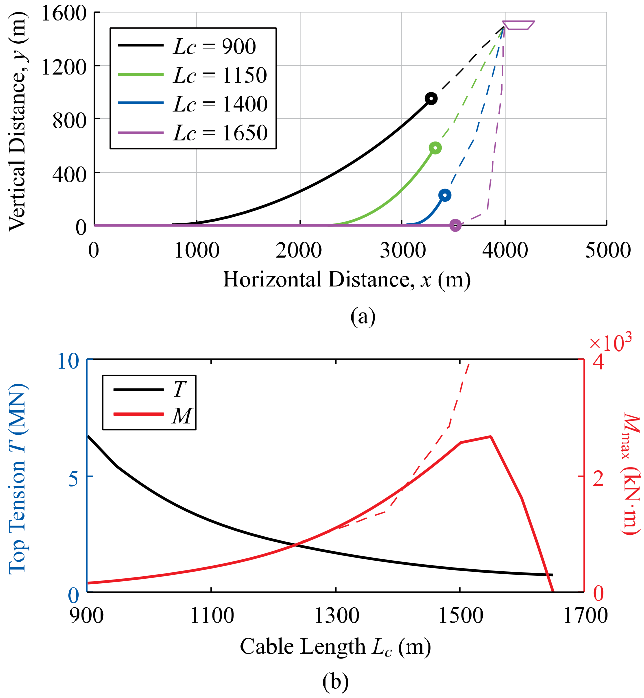

Fig. 9 Analysis results of pipeline abandonment under static vessel position.

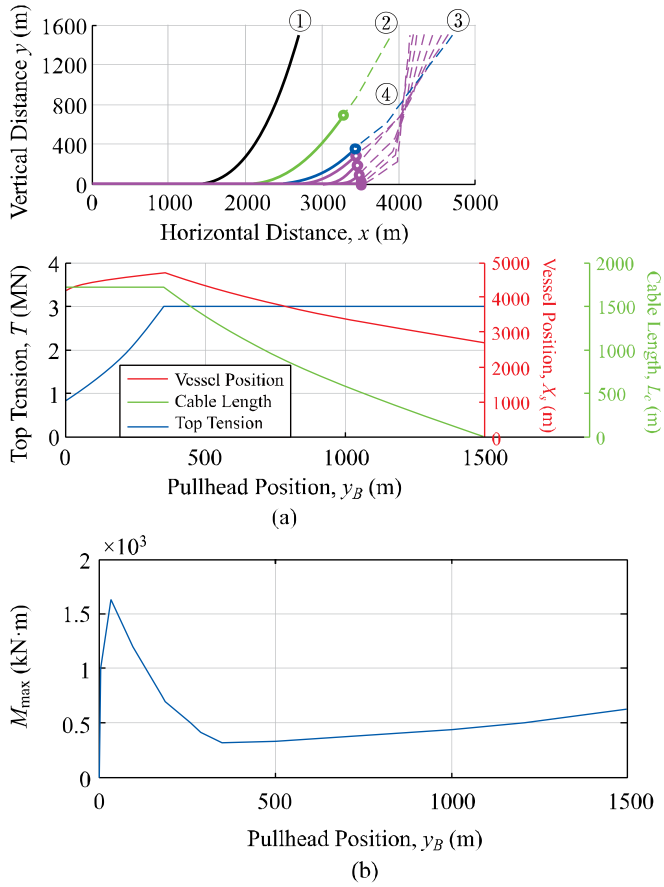

Fig. 10 Analysis results of pipeline abandonment with the first strategy.

The cable-pipeline profiles for different top tensions are plotted in Fig. 8a. It shows that the vessel slightly moves forward (to the right) while the top tension increases. Fig8b shows the effects of top tension on the cable length and the maximum pipeline bending moment. With constant cable length, the maximum bending moment decreases when the top tension increases. The accuracy of the simplified method and the proposed method are also compared in this case. Fig. 8b shows the variation of the vessel position and the maximum bending moment with the top tension obtained using the two methods (the simplified method indicated by the dashed line). It is shown that the simplified method tends to overestimate the maximum bending moment and underestimate the vessel moving distance in this case.

3. Effects of Cable Length

In all the simulations to analyze the cable length effects, the vessel to pipeline end distance is maintained at X_s= 4000 m. The top tension changes with the cable length.

The cable-pipeline profiles for different cable lengths are plotted in Fig. 9a. It shows that the pipeline is lowered as the cable length increases. Fig 9b shows the effects of cable length on the top tension and the maximum bending moment in the pipeline. The maximum bending moment increases with the cable length, but it starts to decrease when the pull-head is close to the seabed and finally decreases to zero when the pipeline is fully abandoned. Fig 9b also shows the comparison between the proposed method and the simplified method (indicated by the dashed line). The two methods show little difference in evaluating the variation of top tension with the cable length, but a significant difference in the maximum bending moment. The simplified method tends to significantly overestimate the maximum bending moment when the pull-head is close to the seabed.

IV. COMPARISON OF A&R STRATEGIES

The procedures of pipeline abandonment should be carefully analyzed before the operation. In this section, three abandonment strategies are studied.

(1) In the first strategy, the abandonment process is divided into two phases. In the first phase, the top tension is maintained at a constant, and the cable length increases to lower the pipeline. In the second phase, the cable length is maintained at a constant, and the vessel moves until the pipeline is fully abandoned.
(2) The second strategy is also divided into two phases. The first phase is the same as in the first strategy. However, in the second phase, the vessel position stays unchanged, and the cable length increases to lower the pipeline.
(3) The third strategy is designed to keep the maximum bending moment within a certain range. In this strategy, the pipeline is abandoned by iterating the processes of static

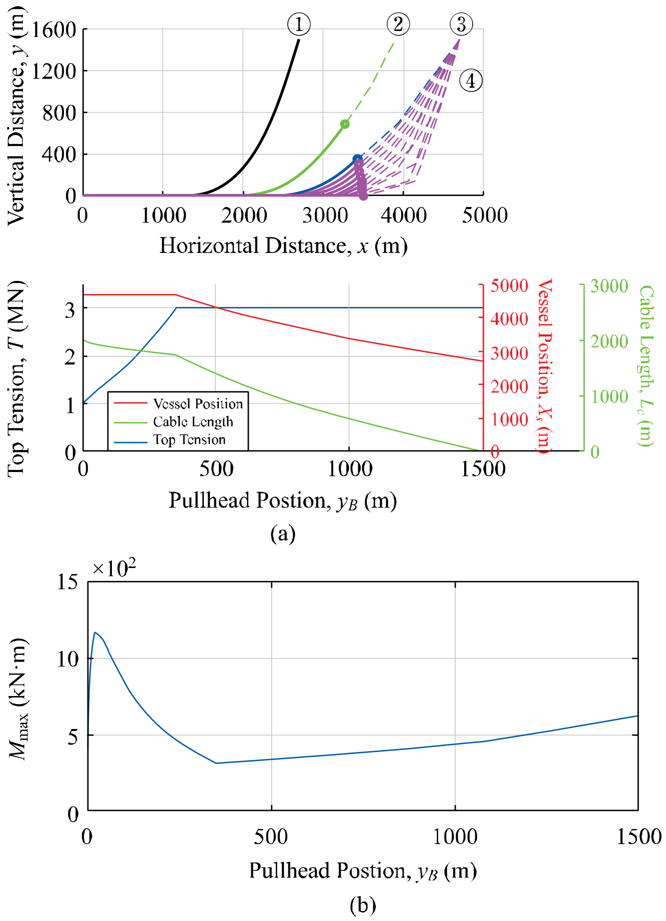

Fig. 11 Analysis results of pipeline abandonment with the second strategy.

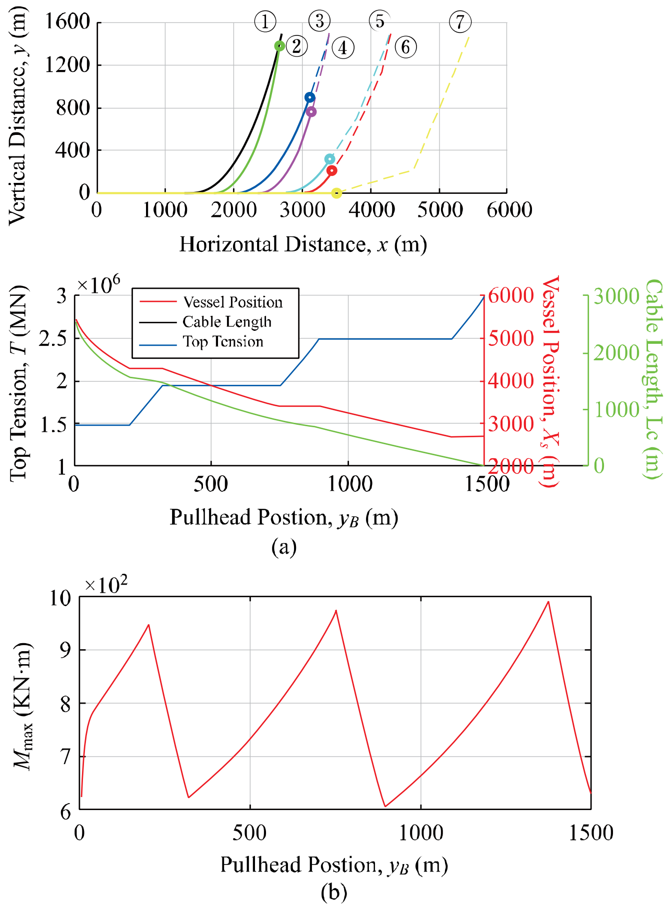

Fig. 12 Analysis results of pipeline abandonment with the third Strategy.

vessel and constant tension: 1) The pipeline is first lowered as the vessel stays stationary until the maximum bending moment exceeds the designed upper margin; 2) then, the pipeline is lowered as the top tension remains unchanged until the maximum bending moment exceeds the designed lower margin.

1. The First Strategy

In the first strategy, the top tension is first maintained at a constant ($T_s = 3.0\times 10^6$ N), and the vessel moves forward by a distance of 2000 m, from the original position 1 to position 3, as shown in Fig. 10a. In this process, the cable length keeps increasing and the maximum pipeline bending moment keeps decreasing. In the second phase, the cable length is maintained, and the vessel position moves slightly backward. At the same time, the top tension decreases. As shown in Fig. 10b, the maximum bending moment sharply increases but dramatically decreases when the pull-head gets close to the seabed.

2. The Second Strategy

As shown in Fig. 11, in the second strategy, the top tension is also maintained as the vessel moves from the original position to position 3 in the first phase. However, in the second phase, the vessel position stays unchanged, and the cable length increases slightly while the top tension decreases significantly. Similarly, the maximum bending moment increases sharply and then decreases dramatically when the pull-head gets close to the seabed. Compared to the first strategy, the second strategy needs more cable but induces a lower bending moment in the pipeline.

3. The Third Strategy

In the third strategy, the maximum bending moment is set to be in the range from 600 kN · m to 1000 kN·m. As shown in Fig. 12, the process is marked by 7 stages. From stage 1 to stage 2, the vessel stays static while the pipeline is lowered, and the maximum bending moment increases. When the maximum bending moment exceeds the upper range, the vessel starts to move forward while the top tension is maintained to reduce the maximum bending moment. From stage 2 to stage 3, the pipeline is lowered until the maximum bending moment exceeds the lower margin. To maintain the maximum bending moment within the designed range, the process is iterated (i.e., stage 3 to stage 5 and stage 5 to stage 7).

In the third strategy, the maximum bending moment in the whole abandonment process is significantly reduced.

However, compared to strategies 1 and 2, the vessel moves a longer distance and more cables need to be used.

V. CONCLUSIONS

In this paper, a mathematical model for deep-water pipeline abandonment analysis is proposed based on the large deflection beam theory. An efficient solution technique is proposed, which makes the initial guess through the two-catenary method and incorporates the moving boundary technique. Some parametric studies of the dominant parameters and comparison of the A&R strategies are conducted with the proposed approach. The present study is of great significance to the future design of A&R procedures. The following general conclusions are drawn.

(1) Based on the large deflection beam theory, the pipeline and cable share the same governing equations but involve different bending rigidities. In the present approach, the moving boundary technique proposed by Zeng et al. (2014) can effectively solve the suspended pipeline section. Adopting the results obtained with the simplified two-catenary method as the initial guess can significantly accelerate the solution process of the present model.

(2) The process of pipeline abandonment is analysed. If the top tension is constant, the cable length increases, and on the opposite side, the maximum bending moment decreases, as the vessel moves forward. If the cable length is constant, the vessel slightly moves forward and the maximum bending moment decreases, while the top tension increases. If the vessel stays static, the top tension decreases and the maximum bending moment increases as the cable length increases, but the maximum bending moment dramatically decreases when the pull-head approaches the seabed.

(3) Among the three abandonment strategies studied, the third strategy shows great advantages. By repeating the process of static vessel – constant tension, it can effectively keep the maximum bending moment within the designed range

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