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Recommended Citation

Han, Duanfeng; Huang, Kuo; Zan, Yingfei; and Wu, Zhaohui (2017) "A NUMERICAL MODEL FOR PIPELINE ABANDONMENT IN DEEP WATER," *Journal of Marine Science and Technology*: Vol. 25 : Iss. 6 , Article 17.

DOI: 10.6119/JMST-017-1226-17

Available at: <https://jmstt.ntou.edu.tw/journal/vol25/iss6/17>

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Acknowledgements

The authors would like to express their gratitude to the Fundamental Research Funds for the Central Universities (HEUCFJ170103) and the Marine Engineering Equipment Scientific Research Project of Ministry of Industry and Information Technology of PRC for the financial support for this study.

A NUMERICAL MODEL FOR PIPELINE ABANDONMENT IN DEEP WATER

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Key words: pipeline abandonment, J-laying, numerical iterative method, catenary model, parametric study.

ABSTRACT

In offshore oil and gas engineering, pipeline abandonment is unavoidable and its mechanical analysis is necessary and important. For this problem, a numerical model is developed in this study to evaluate pipeline abandonment for the J-laying method. The whole system considered in this model is divided into two parts: the A&R cable and the pipeline in the water. A catenary model was proposed for the former, and the latter is solved by a numerical iterative method. In addition to the boundary conditions at the two end points, a special set of boundary conditions is required at the junction that connects the cable and the pipeline. Furthermore, a parametric study is performed to study the effect of the length of the pipeline, the horizontal distance between the two end points, the pipe-cable length ratio, and the depth of water on the pipeline abandonment. The proposed model can help develop deepwater pipeline abandonment and analysis.

I. INTRODUCTION

Pipeline abandonment is an important part of offshore oil and gas engineering. There are two situations in which abandonment is necessary. First, pipelines are abandoned after they are laid and prior to the arrival of the platform. Second, pipelines are abandoned during exceptionally rough sea conditions in the process of the laying of the pipeline. Today, two methods are primarily used for pipelaying: the S-laying method, used for pipelaying at shallow depths, and the J-laying method, used for pipelaying at deep depths (Poberezhnyi et al., 2016). The J-laying method is regarded as one of the most feasible methods to lay a pipeline in deep water (Zan et al., 2016a). When it comes to pipeline abandonment in deep water, in most cases it refers to abandonment for the J-laying method.

The abandonment operation consists of gradually lowering the

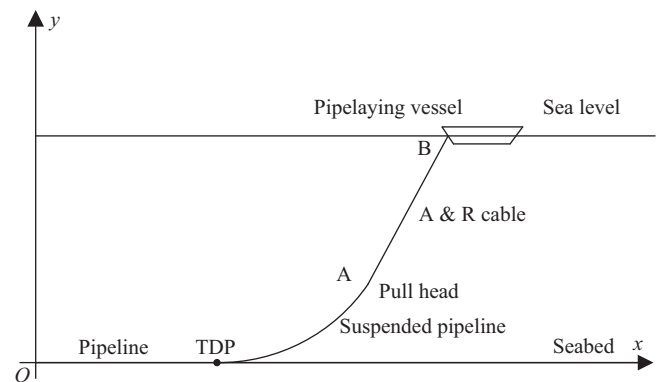


Fig. 1. J-laying abandonment operation.

suspended portion of the pipe to the seabed from the sea surface with the help of an A & R cable (Fig. 1). In the process the pipeline is put down to the seabed from the sea surface by joint A, a pull head fixed to the cable. The pipe extends between an unknown, variable touchdown point (TDP) on the seabed and the cable connected to joint B, a winch on the pipelaying vessel (Andreuzzi and Maier, 1980). During abandonment, the configuration and the internal tension force of the pipe and cable always have to be the prime concern. The pipeline and cable must not overstress during the operation in order to prevent strength damage. Thus, analysis of the pipeline and cable is necessary.

There has been considerable literature devoted to the subject of analyzing the pipeline and cable system during laying. Plunkett (1967) first modelled the pipeline with the catenary method and found a formal asymptotic expansion valid for large, nonlinear deflection with the condition that the tension has more influence than the bending stiffness over most of the length. On the basis of that, other researchers used a stiffened catenary method to solve the pipeline laying problem (Dixon and Rutledge, 1968). Lenci and Callegari (2005) developed three simple analytical models for the J-laying problem. By these models, the boundary layer phenomenon was detected and the influence of soil stiffness was studied. Kang et al. (2015) focused on the J-laying of a steel catenary riser and proposed a new model using the sectional mechanics model by iterating and composing the catenary method and large deflection method. Poberezhnyi et al. (2016) estimated the residual lifetime of metal used for offshore gas pipelines under a low amplitude cyclic load applying S- and J-

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methods for pipelaying. Zan et al. (2016b) presented a real-time numerical model for the dynamic analysis of an offshore pipeline in a J-laying simulation. In addition, Gong et al. (2011, 2014, 2016a, 2016b) performed several analyses on the deepwater S-laying method and studied the influences of pipe-soil interaction and sea state on deepwater S-laying.

However, there has been relatively little work devoted to the issue of pipeline abandonment. Andreuzzi and Maier (1980) developed a simple, computationally economical procedure for approximate comparative static analysis of abandonment-recovery operations. They employed numerical results in nondimensional variables to construct diagrams that make it possible to visualize the evolution of the main static and geometric quantities along alternative abandonment and recovery processes. Datfa (1982) adopted the finite difference method for the purpose of analyzing the pipeline, and for the cable length attached to the pipeline, he employed a line integration technique. Dai et al. (2000) studied the deformation of the pipeline by using the spline collocation method while the cable attached to the pipeline was analyzed by employing a line integration technique. Zeng et al. (2014) proposed a novel technique for the handling of the moving boundary condition without contact analysis. Mao et al. (2014) set up models for the touchdown segment and spanning section using the elastic foundation plate theory and the non-linear beam theory, respectively, to analyze the mechanical behaviors of pipeline undergoing abandonment and recovery operations. Wang et al. (2015) proposed a comprehensive mechanical model based on the nonlinear large deformation beam theory for simulating the steel lazy-wave riser in deepwater and developed a simple and suitable model for analyzing the A & R cable.

In this paper, to evaluate pipeline abandonment for the J-laying method, a numerical model is developed on the basis of previous studies (Irvine and Ma, 1981; Senthil and Selvam, 2015; Samadi and Hassanabad, 2017). Although a single model can never be used to simulate the entire process, the whole system considered in this model is divided into two parts: the A & R cable and the pipeline in the water. A catenary model was proposed for the cable part and the pipeline is solved by a numerical iterative method. The shape and variation of the internal force of the pipe and cable under different operating conditions are analyzed.

II. MATHEMATICAL MODEL

During the abandonment of a submarine pipeline, since the cable and a part of the pipe are suspended in water, their weights lead to a tension force at the winch, which is also the releasing point of the cable. The pipe is gradually laid down on the seabed by changing, as governing independent variables, two of the following three parameters that are available and easily measurable on the barge:

- (1) The cable tension T at the winch
- (2) the position of the barge with respect to the laid pipe along the laying route, a position that is defined here by the distance

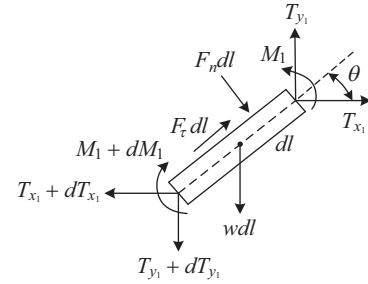


Fig. 2. Force analysis of a pipeline element suspended in water.

X between the stern pulley for the cable C (usually on the stinger) and the location of the pulling head P on the seabed after abandonment

- (3) the length L_c of the cable from the aft pulley to the pipe head

Given two of these parameters and the fixed data that characterize the situation (seabed profile, sectional properties of the pipe and cable), the static equilibrium configuration and the stress state of the system, including the third parameter, can be defined.

1. Model for the Pipeline

A differential element of the pipeline is shown in Fig. 2. By neglecting the high-order force terms and performing the force analysis for the differential element, we can obtain the following governing equations for the pipeline:

$$\begin{aligned} dT_{x_1} &= F_n dl \sin \theta + F_r dl \cos \theta \\ dT_{y_1} &= F_r dl \sin \theta - F_n dl \cos \theta - w dl \\ dM_1 &= T_{y_1} dl \cos \theta - T_{x_1} dl \sin \theta \end{aligned} \quad (1)$$

where T_{x_1} and T_{y_1} represent the horizontal and vertical components of the tension force, respectively, θ is the inclination angle of the pipeline between the pipeline axial direction and the horizontal direction, dl is the length of the pipeline differential element, w is the submerged weight of the pipeline per unit length, M_1 is the bending moment, and F_n and F_r are the horizontal and vertical components of the drag force, respectively.

The pipeline considered here is very long and it becomes flexible in water. The bending moment is negligible in comparison with the tension force. The bending stiffness can thus be neglected. The direct relationship between tension force and the angle θ can be expressed as

$$\tan \theta = T_{y_1} / T_{x_1} \quad (2)$$

If neglecting the axial strain and shear strain of the pipeline, the following geometric relations can be obtained:

$$\begin{aligned} dx_1 &= dl \cos \theta \\ dy_1 &= dl \sin \theta \end{aligned} \quad (3)$$

The pipeline in water is divided into m elements with the same dy_1 along the vertical direction. All elements are considered to be the small elements without curvature. The pipeline on the seabed is divided into n elements with the same dx along the horizontal direction.

For an arbitrary element i of the pipeline suspended in water, the equilibrium relations can be derived in terms of Eq. (1) as follows:

$$T_{x_{i+1}} = T_{x_i} + F_{\tau i} dl_i \cos \theta_i + F_{n i} dl_i \sin \theta_i \quad (4)$$

$$T_{y_{i+1}} = T_{y_i} + F_{\tau i} dl_i \sin \theta_i - F_{n i} dl_i \cos \theta_i - w dl_i \quad (5)$$

$$T_{l_{i+1}} = \sqrt{T_{x_{i+1}}^2 + T_{y_{i+1}}^2} \quad (6)$$

The following geometric relations can be derived in terms of the Eq. (2) and Eq. (3):

$$y_{l_{i+1}} = y_{l_i} + dy_1 \quad (7)$$

$$x_{l_{i+1}} = x_{l_i} + dy_1 / \tan \theta_i \quad (8)$$

2. Model for the Cable

The well-known governing equation for catenary is used to model the segment of cable suspended in water. The governing equation for the pipeline can be expressed as:

$$y_1''(x_1) = \frac{w}{H} \sqrt{1 + [y_1'(x_1)]^2} \quad (9)$$

where $y_1(x_1)$ is the deformed shape, w is the submerged weight of the pipe per unit length, and H is the constant horizontal component on the tension force T .

The general solution of Eq. (1) can be derived by elementary algebra:

$$y_1(x_1) = c_1 + \frac{H}{w} \cosh\left(\frac{w}{H} x_1 + c_2\right) \quad (10)$$

where c_1 and c_2 are unknown coefficients. For the large deflection beam theory, the slope angle, curvature, and tension are then obtained as follows:

$$\theta(x_1) = \arctan[y_1'(x_1)] \quad (11)$$

$$\kappa(x_1) = \frac{d\theta}{ds} = \frac{d\theta}{dx_1} \frac{dx_1}{ds} = \frac{w^3}{H^3 [y_1''(x_1)]^2} \quad (12)$$

$$T_1(x_1) = \frac{H^2}{w} y_1''(x_1) \quad (13)$$

Table 1. Calculation parameters.

Parameters	Value
Submerged pipeline weight, w_p ($N \cdot m^{-1}$)	8101.3
Submerged cable weight, w_c ($N \cdot m^{-1}$)	357
Mod. of elasticity of pipe, E_p ($\times 10^{11} N \cdot m^{-2}$)	2.1
Mod. of elasticity of cable, E_c ($\times 10^{11} N \cdot m^{-2}$)	1.177
Outer pipeline diameter, d_{p1} (m)	1.2
Pipeline thickness, Δd (m)	0.0218
Cable diameter, d_c (m)	0.095
Water depth, D (m)	1250
Horizontal distance between the two end points, X (m)	640
Length of pipeline, L_p (m)	742.15

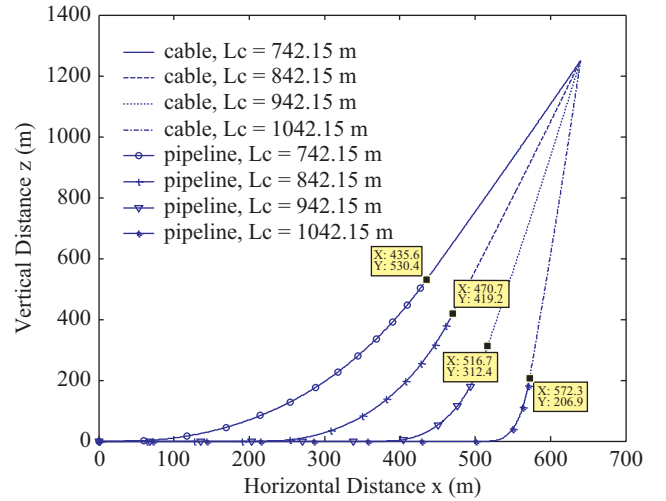


Fig. 3. Comparison of the pipeline configurations for different lengths of the cable.

c_1 and c_2 can be determined by the continuity of the displacement and slope at the junction of the cable and the pipeline.

III. PARAMETRIC STUDY

To illustrate the effects of several parameters on pipeline abandonment, parametric analysis in four cases will be performed in the following sections. To be specific, the effect of the four parameters on the tension in the cable and on the shape of the pipeline will be studied. These parameters are the length of the cable, the horizontal distance between the two end points, the pipe-cable length ratio, and the depth of water. In all four cases, the seabed is assumed to be stiff and the velocity of the current is ignored.

1. Effect of the Cable's Length

In order to study the effect of the cable's length on pipeline abandonment, four different lengths are considered for the cable when the other parameters remain the same. The calculation parameters are presented in Table 1.

The comparison of the pipeline configurations for different lengths of cable is plotted in Fig. 3. The comparison of the ten-

Table 2. Comparison of the tension forces at the releasing top for different lengths.

Length of cable L_C (m)	Total length L (m)	Tension at top T ($\times 10^6$ N)	Angle at top φ_0 ($^\circ$)
742.15	1484.3	6.219	74.48
842.15	1584.3	4.580	78.86
942.15	1684.3	3.274	82.90
1042.15	1784.3	2.183	86.61

Table 3. Comparison of the tension forces at the releasing top for different horizontal distances.

Horizontal distance X (m)	Tension at top T ($\times 10^6$ N)	Angle at top φ_0 ($^\circ$)
440	4.900	83.90
540	5.428	79.53
640	6.219	74.48
740	7.754	68.35

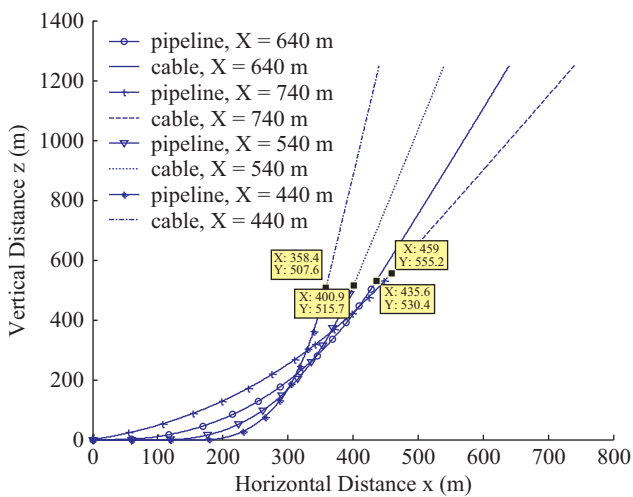


Fig. 4. Comparison of the pipeline configurations for different horizontal distances.

sion forces and angles at the point of release for different lengths is presented in Table 2.

As shown in Fig. 3 and Table 2, the tension force at the releasing top decreases from 6.219×10^6 N to 2.183×10^6 N as the length of the cable increases from 742.15 m to 1042.15 m. However, the top angle increases from 74.48° to 86.61° as the length of the cable increases. In other words, as the length of the cable increases, its orientation becomes increasingly vertical. Furthermore, it can be seen from Fig. 3 that the junction gets closer to the seabed as the cable becomes longer; and the touchdown zone also gets longer.

It can be learned from this case that increasing the length of cable can help decrease the tension in the cable. Since the abandonment operation involves gradually increasing the length of cable by releasing the cable, the conclusion also implies that the tension in cable decreases during the process of pipeline abandonment.

2. Effect of Horizontal Distance between the Two End Points

Just like the study performed for the effect of the cable’s length, four different horizontal distances are considered for the cable and the pipeline when the other parameters remain constant to study the effect of the horizontal distance between the two end points. In this case, the length of the cable is a constant as $L_C = 742.15$ m, which is equal to the length of the pipeline as other calculation parameters remain the same as those described in Table 1.

Fig. 4 shows the comparison of the pipeline configurations for different horizontal distances. And Table 3 shows the comparison of the tension forces and angles at the releasing top for different horizontal distances.

As we can see in Fig. 4 and Table 3, the tension force at the releasing top has an increase from 4.900×10^6 N to 7.754×10^6 N as the horizontal distance increases from 440 m to 740 m. The top angle simultaneously decreases from 83.90° to 68.35° . Moreover, the touchdown zone is shorter for longer horizontal distances. Thus, decreasing the horizontal distance between two end points moderately can help decrease the tension in the cable when the lengths of the pipeline and the cable are fixed.

3. Effect of the Pipe-Cable Length Ratio

In order to study the effect of the pipe-cable length ratio on pipeline abandonment, four different ratios are considered for the cable and the pipe in this case when the other parameters stay the same. The total length of the pipe and the cable remains constant at 1484.3 m. The other calculation parameters are the same as those described in Table 1.

The comparison of the pipeline configurations for different pipe-cable length ratios is plotted in Fig. 5. The comparison of the tension forces and angles at the releasing top for different pipe-cable length ratios is presented in Table 4.

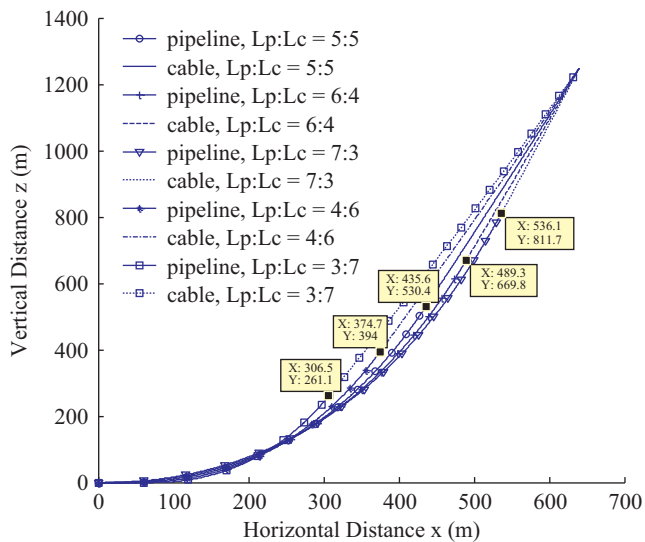
Fig. 5 and Table 4 show that the tension force at the releasing top increases from 3.546×10^6 N to 8.727×10^6 N as the pipe-cable length ratio increases from 3/7 to 7/3. The top angle in-

Table 4. Comparison of the tension forces at the releasing top for different pipe-cable length ratios.

Pipe-cable length ratio	Length of pipe L_P (m)	Length of cable L_C (m)	Tension at top T ($\times 10^6$ N)	Angle at top φ_0 ($^\circ$)
3:7	445.29	1039.01	3.546	72.34
4:6	593.72	890.58	4.906	73.33
5:5	742.15	742.15	6.219	74.48
6:4	890.58	593.72	7.490	75.65
7:3	1039.01	445.29	8.727	76.79

Table 5. Comparison of the tension forces at the releasing top for different depths.

Water depth D (m)	Tension at top T ($\times 10^6$ N)	Angle at top φ_0 ($^\circ$)
1150	4.661	77.78
1200	5.415	76.09
1250	6.219	74.48
1300	7.278	72.64

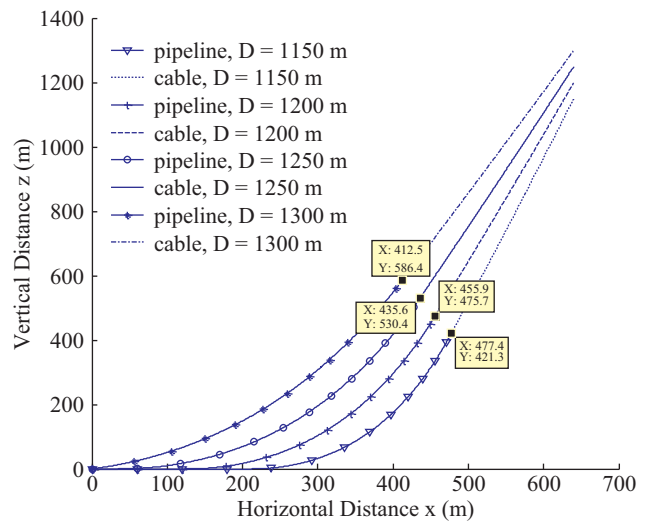
**Fig. 5. Comparison of the pipeline configurations for different pipe-cable length ratios.**

creases from 72.34° to 76.79° as the pipe-cable length ratio increases. The length of the touchdown zone increases as well. It can be concluded from this case that a smaller pipe-cable length ratio can help decrease the tension. In other words, shorter lengths of pipe with longer cable produce less tension. This finding reinforces the conclusion from the first case.

4. Effect of the Water Depth

In order to determine the effect of water depth on pipeline abandonment, four different depths are considered for abandonment in this case. The length of the cable remains constant at $L_C = 742.15$ m. The other calculation parameters are the same as those described in Table 1.

In Fig. 6 there is the comparison of the pipeline configurations for different depths. In Table 5 the comparison of the tension

**Fig. 6. Comparison of the pipeline configurations for different depths.**

forces and angles at the releasing top for different depths is presented.

From Fig. 6 and Table 5 we can see that the tension force at the releasing top increases from 4.661×10^6 N to 7.278×10^6 N as the water depth increases from 1150 m to 1300 m. The top angle decreases from 77.78° to 72.64° as the water depth increases. The length of the touchdown zone decreases as well. The conclusion drawn from this case is that when the length and horizontal distance are given, operating in deeper water will increase the tension in the cable.

IV. CONCLUSION

A numerical model for pipeline abandonment for the J-laying method in deep water is developed in this paper. The effects of four parameters on pipeline abandonment are studied in detail with the present model. The four parameters considered include

the length of the cable, the horizontal distance between the two end points, the pipe-cable length ratio, and the water depth. All these four parameters impact the tension in the cable and the shape of pipeline during pipeline abandonment for the J-laying method. The tension force at the releasing top, which is the main concern, changes with the alteration of each of the four parameters. It turns out that, among the four parameters, the pipe-cable length ratio has the greatest effect on tension. Longer cable and shorter pipe contribute to a decrease in tension in the cable. Since the length of the pipeline usually cannot be altered during abandonment during pipeline abandonment, the tension force can be decreased by using a longer cable. We can also conclude that when the top angle increases, the length of the touchdown zone decreases, thereby relieving tension at the top.

This paper can help during deepwater pipeline abandonment operations. However, since some assumptions are made for this analysis, further work, for example, on the effect of the load of the wave and current, pipe-soil interaction, and others on pipeline abandonment should be carried out.

ACKNOWLEDGEMENTS

The authors would like to express their gratitude to the Fundamental Research Funds for the Central Universities (HEUCFJ170103) and the Marine Engineering Equipment Scientific Research Project of Ministry of Industry and Information Technology of PRC for the financial support for this study.

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