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Research on Stability Analysis of Bonded Flexible Submarine Pipeline

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Research on Stability Analysis of Bonded Flexible Submarine Pipeline

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Abstract. As an important part of underwater oil and gas transportation system, the in-situ stability of submarine pipelines is particularly important. Comparing with steel pipe, flexible pipe has the advantages of high strength, corrosion resistance, light weight, coil supply and laying. In this paper, the finite element software ABAQUS is used to calculate the initial in-situ stress balance of soil, pipe weight, internal pressure load analysis and horizontal buckling simulation. The transverse horizontal displacement and stress distribution under high temperature and high pressure in flexible pipeline operation are calculated. The results show that the temperature difference and pressure difference in pipeline operation are the main causes of pipeline failure. The results show that the relevant parameters of seabed soil have different effects on pipeline failure, and the friction coefficient of soil and pipeline is more obvious.

1. Introduction

Flexible pipes are divided into bonded flexible pipes and non-bonded flexible pipes. The structure of bonded flexible pipes is mainly composed of reinforcement layer (including skeleton layer, compressive and tensile polymer layer) (including inner sheath layer, outer sheath layer and friction layer between reinforcement layers). At present, steel pipe occupies the main market of natural gas and oil transportation because of cost, usability, strength and reliability [1]. But steel pipe has its limitations, the biggest problem is corrosion, and the weight is large, the cost of laying is high.

With the breakthrough of technology and the development of market, the application of bonded flexible pipes is very extensive, which can be used as dynamic riser, submarine manifold system and floating production system connection, oil pipeline and spanning hose, there is a trend to replace the pure steel pipeline. However, the bonded pipeline is light in weight and bears wave-current hydrodynamic load directly on the seabed [3]. Without considering the additional weight, it may lose stability because of excessive lateral displacement, and buckling failure is more likely than steel pipe. Therefore, combining with the current mainstream code for stability analysis of submarine pipelines, the paper studies the flexibility of the bonded pipeline. The parameters and design methods involved in stability analysis of sex pipelines are of far-reaching significance.

By choosing the counterweight scheme of submarine pipeline and establishing the pipe-soil model with ABAQUS, the in-situ stability of offshore flexible pipeline is analyzed by an example, and compared with DNV code [3], the accuracy of the research method is verified. The factors that have great influence on the in-situ stability of pipeline are analyzed. Finally, the factors that have more obvious influence on pipeline stability are summarized.

2. Theory and Method

2.1. Initial geostatic stress equilibrium

In order to study the in-situ stability of pipelines, it is necessary to balance the initial in-situ stress [2]. The following two conditions need to be satisfied when defining the initial in-situ stress:

(1) Equilibrium condition: Equivalent nodal load formed by stress field should be balanced with external load. If the equilibrium condition is not satisfied, an initial state with zero displacement can not be obtained.

(2) Yield condition: If the initial stress field is applied by directly defining the stress state at the Gauss point, the stress at some Gauss point will often be outside the yield surface.

Based on the above two conditions, a common method to balance the initial in-situ stress is to apply the gravity load to the soil and apply the boundary conditions in accordance with the actual engineering conditions, calculate the stress field under the gravity load, then define the stress field as the initial stress field, and apply it to the original stress field together with the gravity load. By using the initial finite element model, the initial stress field which satisfies the equilibrium condition and does not violate the yield criterion can be obtained, and the initial displacement of each node can be guaranteed to be approximately zero.

2.2. Analysis of pipeline weight

Flexible pipes need to be added more weight because of their lighter weight. According to the absolute stability method in DNV RP F109 (2011) [3], the in-situ stability of flexible pipeline is calculated. Finally, the weight of the pipeline under external environmental loads and considering the depth of the pipeline is obtained. The design basis is that the critical safety factor (safety coefficient of lateral stability) is greater than or equal to 1, and the empty pipe ratio is greater than 1.1. (DNV RP F109 3.2) [3] The proportion of air traffic control in water should be at least greater than 1.1.

$$\mathrm{SG} = \frac{W_{\mathrm{sub}} \cdot 1\mathrm{m} + \frac{\pi}{4} D_0^2 \cdot \rho_{\mathrm{seawater}} \cdot 1\mathrm{m}}{\frac{\pi}{4} D_0^2 \cdot \rho_{\mathrm{seawater}} \cdot 1\mathrm{m}} \tag{1}$$

Where, SG is the specific gravity of empty pipelines, W_{sub} is the weight of the empty pipe in the water, ρ_{seawater} is the density of seawater, D_0 is the pipeline outer diameter. The following is based on the weight of the counterweight per unit length.

$$W_{\mathrm{sub}} + W_{\mathrm{ballast-min1}} = 0.1 \cdot \frac{\pi}{4} D_0^2 \cdot \rho_{\mathrm{seawater}} \tag{2}$$

$$W_{\mathrm{ballast-min1}} = 0.1 \cdot \frac{\pi}{4} D_0^2 \cdot \rho_{\mathrm{seawater}} - W_{\mathrm{sub}} \tag{3}$$

Where, W_{sub} is the maximum weight Required in theory, $W_{\mathrm{ballast-min1}}$ is the minimum weight required in theory.

2.3 Environmental load on the seabed

Wave load is one of the important factors to be considered in submarine pipeline design. For stable ocean currents, the influence of the bottom boundary layer must be considered. Because the position of the velocity boundary layer reduces the effective velocity at the height of the pipeline, the average velocity here can be used for analysis [5]. The DNV code uses average velocity to analyze submarine pipelines and assumes that the velocity curve is a logarithmic curve：

$$v_c = \frac{v_c(z_r)\left(\frac{z_0}{D}+1\right)}{\ln\left(\frac{z_r}{z_0}+1\right)} \left\{ \ln\left(\frac{D}{z_0}+1\right) - 1 \right\} \tag{4}$$

Where, $v_c(z_r)$ is the current velocity of reference point, z_r is the height of reference point to seabed, z_0 is the Bottom roughness parameters, D is the total outer diameter of pipeline.

According to the influence of the factors such as current and wave on the stability of pipeline, the stability of pipeline is analyzed. According to the given environmental parameters, the ocean currents and waves with 100-year recurrence interval are calculated [8]. The velocity of 100-year recurrence interval is 1.75 m/s, and the wave height of 100-year recurrence interval is 12.19m.

2.4. Horizontal buckling analysis of pipeline

Buckling failure is one of the main failure modes of submarine pipelines. Under the action of high temperature and high pressure, the pipeline expands axially, but is limited by soil friction. After a certain distance from the end of the pipeline, the friction between the soil and the pipeline reaches its peak value. Due to the influence of soil properties, the axial friction of pipeline is small, and the pipeline will undergo axial deformation. If the axial friction force is large enough, the axial displacement of the pipeline will be fully constrained. When the axial stress exceeds the critical stress of the pipeline, the overall buckling will occur. In order to simulate this process, two models are introduced.

2.4.1 Temperature stress model

Generally, in order to increase the fluidity of the medium or fluid transported in the submarine pipeline, it is necessary to raise the temperature of the medium or fluid transported [8]. Axial stress of pipeline caused by temperature difference between inside and outside of pipeline can be expressed：

$$\sigma_{lt} = \alpha E \Delta\theta \tag{5}$$

There, σ_{lt} is the axial stress of pipeline caused by temperature difference in pipeline， Mpa; α is the Pipeline expansion coefficient,$E$is the Modulus of elasticity,$\Delta\theta$ is the Temperature difference between inside and outside of pipeline

2.4.2 Internal pressure stress model

In the elastic range, the circumferential stress of the pipeline under internal pressure can be expressed as：

$$\sigma_{cp} = pR/h \tag{6}$$

There，σ_{cp} is the circumferential stress caused by internal pressure,p is the pipeline internal pressure, R is the pipeline inner diameter,h is the pipeline wall thickness.

3. Model establishment

3.1 Pipeline parameter settings

In order to make the model closer to the actual situation, three-dimensional solid model is adopted for pipeline, and Ramberg-Osgood constitutive model is adopted according to material stress-strain relationship. According to the relevant requirements for submarine pipelines in the code for submarine pipeline systems and the code for design of oil pipelines, the parameters of pipelines are shown in Table 1.

Table 1． Pipeline parameters

Diameter (mm)	Wall thickness (mm)	Density (kg/m^3)	Poisson's ratio	Temperature （℃）	Young's modulus （Mpa）
500	40	2360	0.3	40	2100

3.2 Soil parameter settings

The interaction between pipe and soil is complex, so it is very important to choose the appropriate constitutive model of soil [6]. Mohr-Coulomb model is used as the constitutive model to study the interaction between pipe and soil. According to Mohr-Coulomb failure and strength criterion, the parameters of seabed soil model can be found in Table 2.

Table 2． Soil parameters

Young's modulus（Mpa）	Density (kg/m^3)	Cohesion (Mpa)	Poisson's ratio	Friction angle (°)	Friction coefficient
45	1600	15	0.3	25	0.3

3.3 Numerical simulation process

Using ABAQUS analysis and simulation, three loading steps are adopted. The first step is to balance the initial in-situ stress of the soil, so that the initial stress can be obtained by numerical simulation. The second step is to impose self-weight on the pipeline, and to apply uniform concentrated load in the direction of the length of the pipeline, and the third step is to impose internal and external loads on the pipeline. Pressure, the difference between internal and external pressure, and the application of temperature stress to simulate the buckling of the pipeline.

4. Calculation and analysis

4.1 Analysis of calculation results

Modeling of submarine flexible pipeline by ABAQUS software, the horizontal displacement of pipeline is obtained through calculation [4]. The horizontal deformation of pipeline is mainly caused by the axial force caused by the difference of temperature and pressure inside and outside the pipeline. The results are shown in Figure 1.

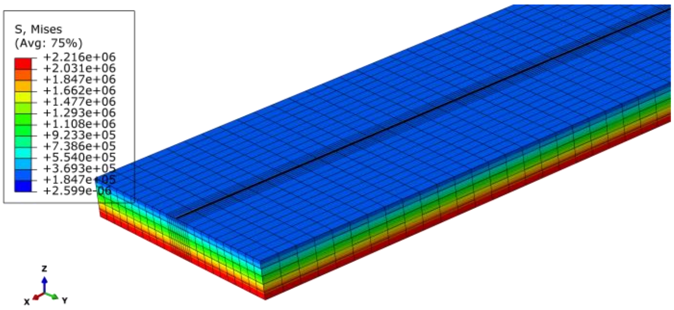

Figure 1. Stress distribution map of integral model

The calculation results show that after initial in-situ stress balance, there is a small displacement in the vertical direction of seabed soil, but compared with the actual project, this displacement can be neglected.

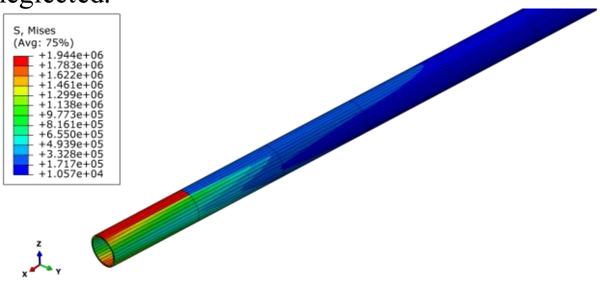

Figure 2. Pipeline stress distribution

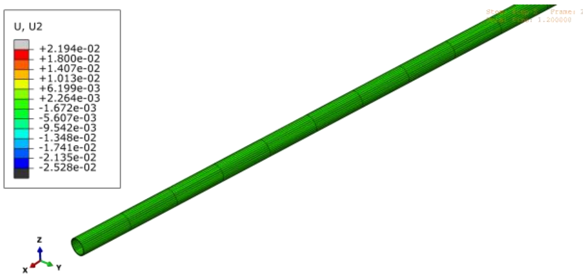

Figure 3. Pipeline transverse displacement

Figure 2 and Figure 3 show the stress distribution and lateral relative displacement of the pipeline under load. When the counterweight and wave load are applied, the lateral stability of the pipeline will be greatly affected, and the seabed soil in contact with the pipeline will also be deformed accordingly.

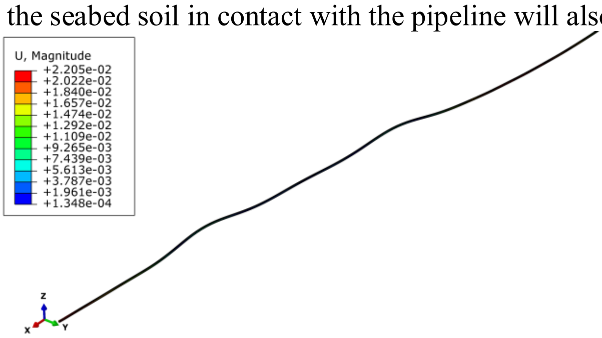

Figure 4. Deformation result of pipeline

The vertical displacement of submarine pipeline also occurs after the self-weight load and buoyancy load of pipeline are applied, resulting in settlement effect. At the same time, it is affected by the self-weight load of the pipeline (Figure 4).

4.2 The influence of parameter changes

By changing the parameters of seabed soil in the model, the pipeline was calculated and analyzed several times. Finally, the horizontal displacement of the pipeline with different parameters is obtained.

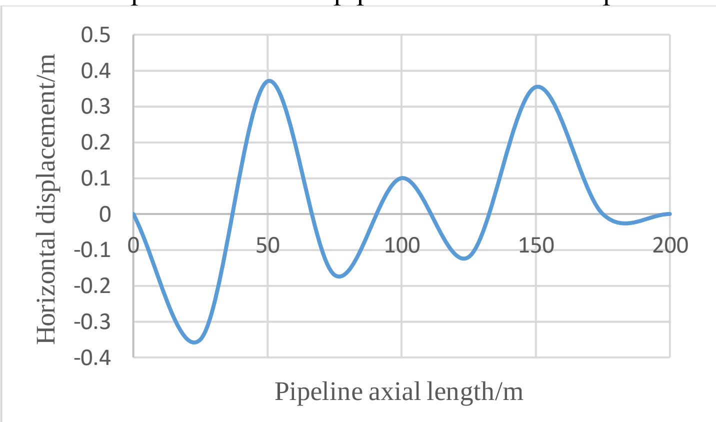

Figure 5. Horizontal displacement of pipeline along axial length

By changing the friction coefficient of the seabed soil in the calculation model, the other parameters are unchanged. The pipeline is calculated and analyzed several times, and the change of the horizontal displacement of the pipeline with the friction coefficient of the soil is finally obtained (Figure 6).

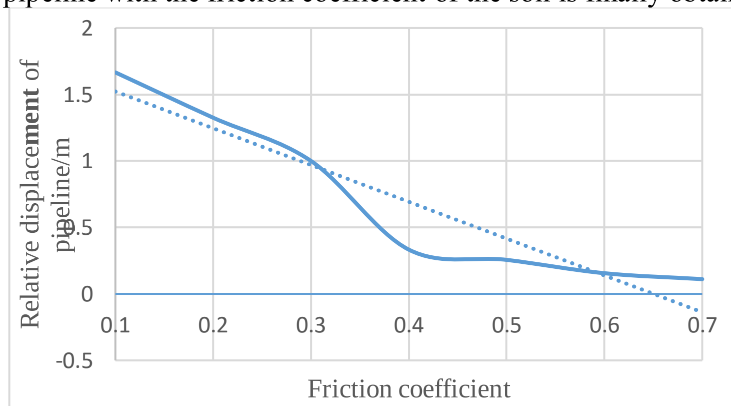

Figure 6. Variation of pipeline horizontal displacement with friction coefficient of soil

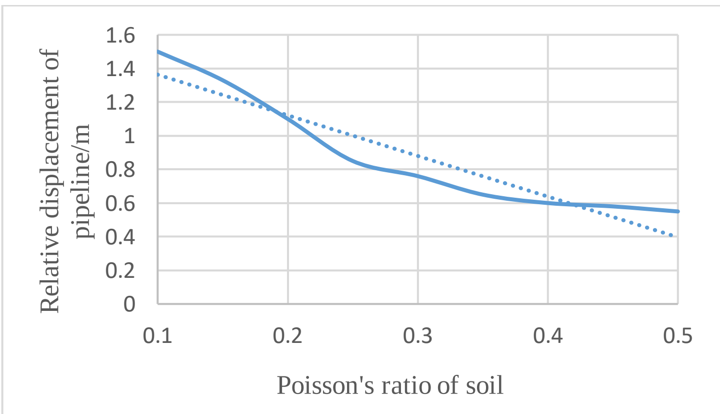

Figure 7. Variation of pipeline horizontal displacement with Poisson's ratio of soil

By changing the Poisson's ratio of seabed soil in the calculation model, the horizontal displacement of pipeline with the Poisson's ratio of soil is calculated, as shown in Figure 7. After calculating the Poisson's ratio of different seabed soils, the relative displacement in horizontal direction keeps between 0.2 m - 0.5 m, and decreases with the increase of Poisson's ratio.

5. Conclusions and recommendations

In this paper, ABAQUS software is used to simulate the working state of cohesive flexible submarine pipeline. Through the analysis of in-situ stress balance, self-weight load and reasonable selection of counterweight, setting of pipe-soil interaction, internal pressure load analysis and horizontal buckling analysis, the transverse direction of submarine pipeline under high temperature and pressure is calculated. Relative displacement and stress distribution are calculated by changing model parameters several times, and the factors that have great influence on the lateral relative displacement of pipeline are obtained.

(1) In the operation of cohesive pipeline, the horizontal deformation is mainly caused by the axial expansion force caused by the difference of temperature and pressure inside and outside the pipeline, and the final displacement is affected not only by the axial force, but also by the horizontal restraint of soil on both sides of the pipeline.

(2) Comparing the results of calculation, it is found that the Poisson's ratio of seabed soil and the friction coefficient of soil and pipeline have different effects on the final deformation of pipeline, and the degree of influence depends on the lateral resistance of soil to pipeline. Among these parameters, the friction coefficient of pipeline and Poisson's ratio of soil have the greatest influence on the variation of pipeline. In the actual process of pipeline installation, special attention should be paid to the parameters of soil and the selection of regions with large stiffness of seabed soil can effectively ensure the stability and safety of pipeline operation.

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