Study on the Impact Damage of Submarine Pipelines by Anchor under Emergency Anchorage

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Abstract. In this article finite element modeling of anchor and submarine pipeline under the condition of emergency anchorage were built up by using ABAQUS software, then numerical simulations were made. Security of the pipeline was checked according to the ratio of the dent depth and pipe wall diameter after that. At the same time the relationships between towing anchor collision damage and pipe wall thickness as well as pipeline slenderness ratio were got by horizontal comparison. It was concluded that the damage degree of the towing anchor is reduced with the increase of thickness and slenderness ratio of the pipelines. Then vertical impact between dropping anchor and pipeline was analyzed by ABAQUS also. Finally, values of DNV specification rules were compared with the numerical simulation results. The research conclusions have some practical significance for the analysis of deformation regularity of the submarine pipelines damaged by the anchor, the design and repair of the pipelines.

1. Introduction

With the rapid development of economy, the exploitation and utilization of oil and natural gas resources has become an important part of China's modernization drive. According to incomplete statistics, there are 315 submarine pipelines (diameter 50.8mm~762.0mm) in China's sea area from 1986 to 2016, and the total length is about 6202km [1]. Because the submarine pipeline is in a bad environment for a long time, it needs to bear complex loads such as environmental load, working load and unexpected risk load, so the risk of pipeline leakage accident is gradually increasing with the rapid development of the marine oil and gas industry. According to statistics, 50 to 60 percent failure of the global submarine oil and gas pipeline rupture has been caused by the damage of the third party, and the ship anchoring operation is one of the most important causes of it. The possible damage of anchor to the submarine pipelines is ducting, piercing and tearing. The damage of Boxi natural gas pipeline in 2008 was a typical accident of ship anchorage damage, which led to the breakage and leakage of the pipeline and caused the whole pipeline to stop. Therefore, in order to ensure the safe transportation of oil and gas and prevent the leakage of the submarine pipeline, it is very necessary to study the damage probability and degree of the anchorage operation on the submarine pipeline.

Compared with the common anchor operation, the speed of anchoring to the bottom of the emergency situation is usually greater than that of the normal anchorage, and the impact force of the anchor on the seafloor will also increase [2]. The impact damage of submarine pipelines under emergency anchorage is divided into two kinds: the impact of dropping anchor and the impact of towing anchor. Under the condition of dropping anchor, the anchor is just at right angle to the submarine pipeline from top to bottom, so the forces of anchor and additional mass are perpendicular to the pipeline also, which will cause greater damage, but the probability is low. On the other hand, when the anchor is dragged along, the anchor and additional mass forces act on the pipeline at a certain angle, although the damage is smaller than the former, but the probability is much higher.

To sum up, in this paper RISK ASSESSMENT OF PIPELINE PROTECTION (DNV-RP-F107) of the Det Norske Veritas (DNV) and the ABAQUS software are used to simulate and compare the impact damage of the anchor to the submarine pipelines under the emergency anchoring situation.

2. Classification of Damage Degree of Submarine Pipelines

The damage classification of exposed pipelines is regulated by DNV-RP-F107 [3]. The grading recommendation is based on the damage level of the submarine pipeline, the energy absorbed by the pipeline and the conditional probability of various damages.

The risk assessment of pipeline protection specification divides the damage into following three levels:

1) Minor damage (D_1): the maximum dent is less than or equal to 5% of the pipe diameter, and the submarine pipeline can run as usual. At this time, oil and gas will not leak, and the pipeline will not need any repair. However, technical inspection must be carried out to ensure that the structure of the sea pipe is complete and can be cleaned normally.

2) Medium damage (D_2): The maximum depth of the dent is greater than 5% and less than or equal to 15% of the pipe diameter, but the leakage of the pipe will not occur. The repair of the submarine pipeline can be delayed for a certain time, but the integrity test of the pipeline should be completed before the next operation.

3) Heavy damage (D_3): Under this condition, the submarine pipeline has been leaked, and the wall of the pipe has been damaged. It is necessary to repair or replace the pipeline immediately, and stop the transportation of oil and gas at the same time.

3. Selection of Sea Area and Anchor

Bohai Bay is one of the main producing areas of China's offshore oil, and the pipeline is complex and dense. In recent years, the shipping industry and fishery have also developed rapidly. The number of ports and berths is increasing, the scale is expanding, and the anchorage operation is more frequent. In addition, Bohai is also one of the major fishery areas in China. In some places, the areas of fishery production may overlap with the submarine pipeline laying areas. These factors will bring a certain risk to the submarine pipeline. According to the statistics from 1986 to 2016, there were 51 accidents of submarine pipelines in the sea area of China, which caused the most accidents in Bohai because of the destruction of the third party.

In summary, a medium sized fishing boat sailing in Bohai waters is selected to be the research object of this article. The ship is equipped with a 5250kg C type Hall anchor. The main parameters of the anchor can be obtained by referring to GB/T 546-1997 [4]: distance between the anchor tips A_A is 1364mm, width of the anchor B_A is 1910mm, length of the anchor shank C_A is 2728mm, length of the flukes D_A is 1760mm, thickness of anchor E_A is 846mm, then the water retaining area S_A can be calculated according to formula (1).

$$S_A = \left(D_A + C_A \sin 45^{\circ}\right)B_A \tag{1}$$

So,

$$S_A = \left(D_A + C_A \sin 45^{\circ}\right)B_A = \left(1760 + 846 \times \frac{\sqrt{2}}{2}\right) \times 1910 = 4.50\text{m}^2$$

4. Impact Damage Analysis of Towing Anchor to Submarine Pipeline Based on ABAQUS

4.1. Establishment and Parameter Setting of Finite Element Model for Towing Anchor Impact Analysis

Fig. 1 is the impact analysis model of towing anchor to submarine pipeline, which is mainly composed of two parts: anchor and pipeline. The towing anchor is modeled according to the above detailed dimensions, and the pipe model is a circular tube with outside diameter of 273.1mm.

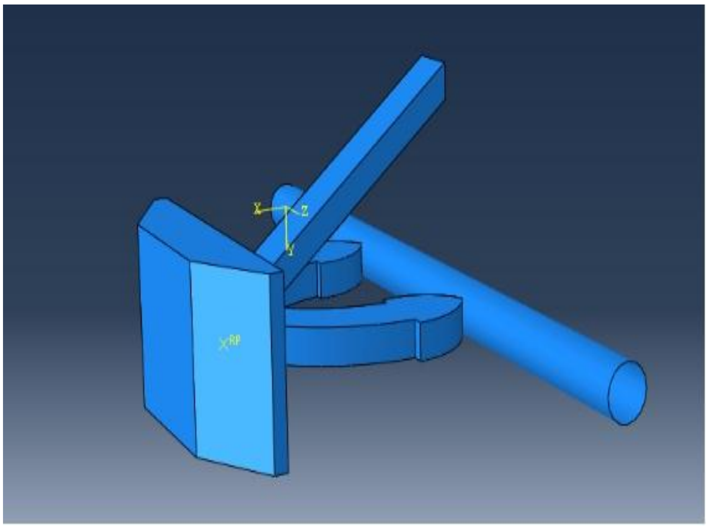


Figure 1. Impact analysis model of towing anchor to submarine pipeline.

In the parameter setting of material, the anchor is set to 3D analytic rigid stretching body, the submarine pipeline is set to 3D deformable and solid stretch shell, and the model selects the elastic-plastic constitutive relation. The masses of towing anchor and the attached water are simulated by adding a concentrated force to the position of the centroid (the point is set as a reference point). The setting of the initial parameters of the impact model is shown in Table 1.

Table 1. Initial parameters of the towing anchor - pipeline impact model.

Item	Value
Pipe outside diameter (D)	273.1mm
Pipe wall thickness (t)	11.1mm, 15.4mm, 19.7mm
Pipe length (L)	5m, 8m, 10m
Steel grade	APIX65
Yield strength (σ_y)	530 MPa
Material density (ρ)	7.85×10^3 kg/m^3
Modulus of elasticity (E)	2.01×10^5 MPa
Poisson ratio (μ)	0.3
Constitutive relation	elastic-plastic

The dynamic explicit analysis is used to simulate the impact process of the towing anchor to the submarine pipeline. The impact of the anchor to the submarine pipeline is a kind of contact problem with typical nonlinear boundary condition. The contact type belongs to the surface contact, the anchor is the leading surface, the pipe is selected as following surface, the contact area includes all of the outer surfaces [5], and the contact interaction is selected as the finite slip. Large deformation switch Nlgeom is set to ON, time increment and other control parameters are taken as default values.

In terms of boundary conditions, both ends of pipeline are rigid fixed, that is the displacement and angles are all 0. It is selected to be the most dangerous situation that the front of anchor tips is impacted on the wall of the tube. The towing anchor is allowed to move in the X axis to ensure that it is positive collision. The speed of the anchor movement is simulated by adding a velocity field at its centroid [6]. Because the speed of the towing anchor is lower than that of the dropping anchor, the speed of 1.5 m/s is chosen as the speed of its impact on the submarine pipeline.

In order to ensure convergence effect and improve the accuracy of computation, the grid is properly thickened in the impact area of the pipeline [7]. The finite element mesh after thickening is shown in Fig. 2. In terms of grid typesetting, the anchor is simulated by R3D4 rigid body element, and the pipe is modeled by S4R shell element.

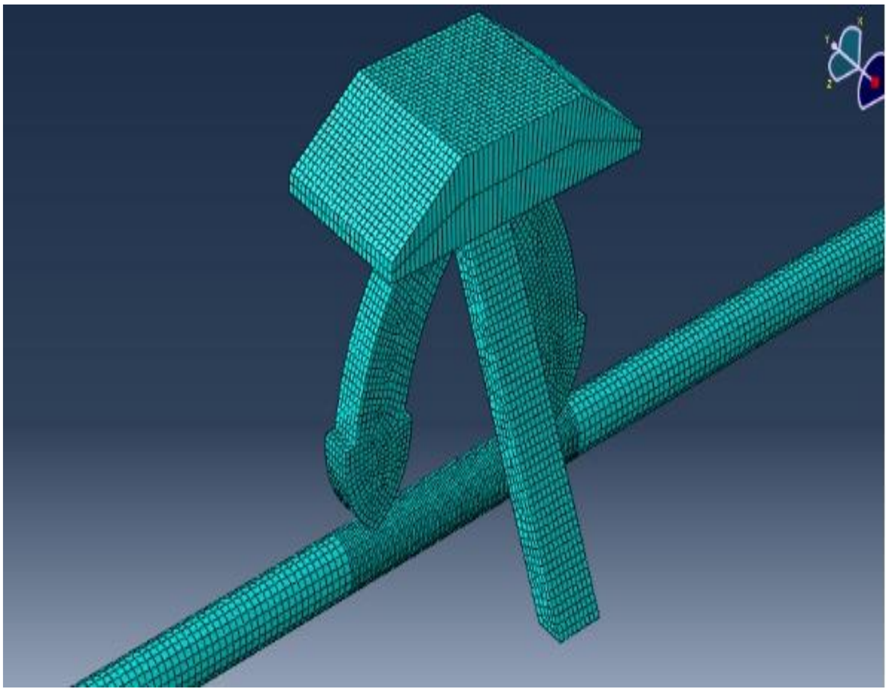


Figure 2. Impact analysis model of towing anchor to submarine pipeline.

4.2. Study on the Relationship between Pipeline Wall Thickness and Impact Damage Degree of Towing Anchor

The impact process of towing anchor on submarine pipeline can be simulated by the finite element model established above. In order to obtain the relationship between the thickness of pipe wall and damage degree of the anchor impact, it is needed to get the plastic deformation of submarine pipelines after collision in different wall thicknesses with the same towing anchor weight of 5250kg. The wall thickness of the submarine pipeline t is 11.1mm, 15.4mm and 19.7mm respectively, and the outer diameter D is 273.1mm.

The global deformation cloud atlas of the submarine pipeline after impact is shown in Fig.3, and the collision area deformation maps are shown in Fig.4.

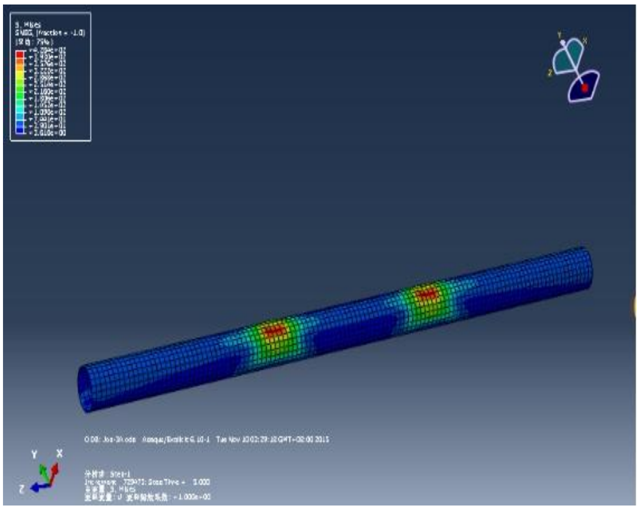
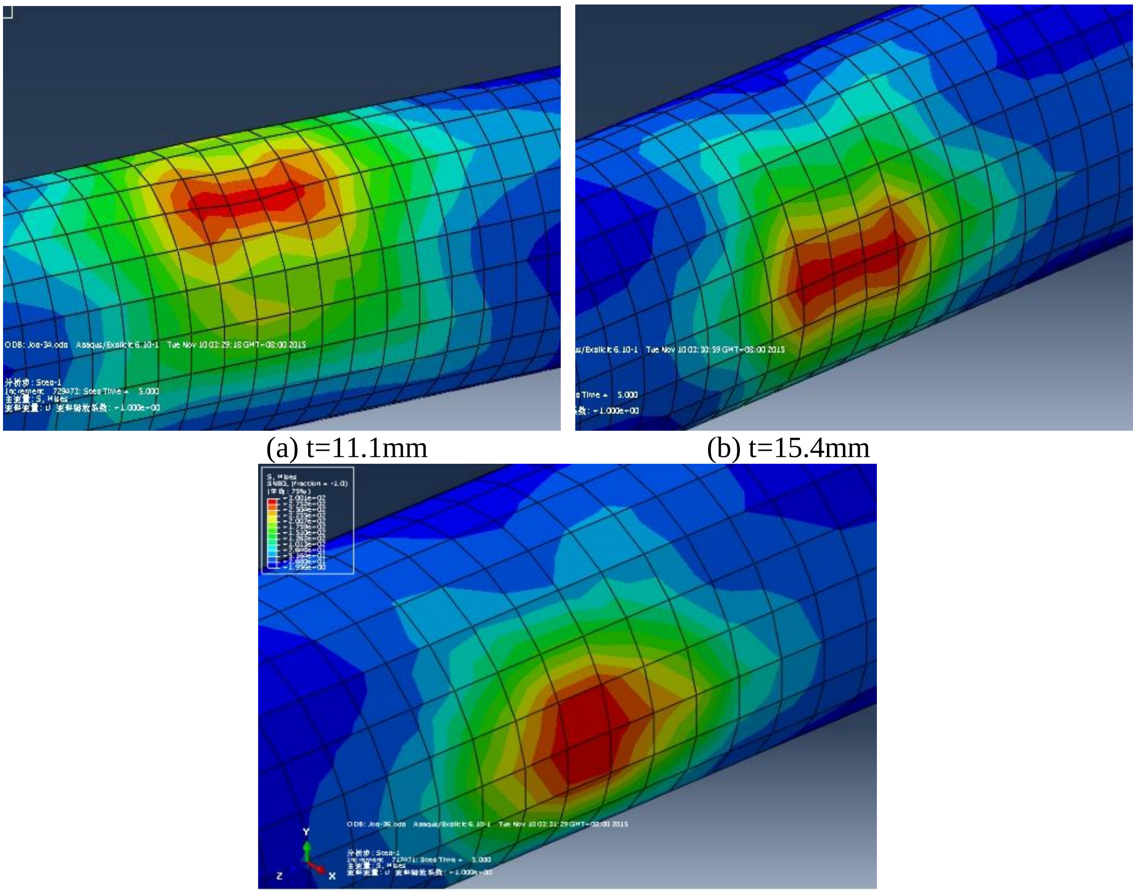


Figure 3. Global deformation cloud atlas of pipeline after impact (t=11.1mm, L=5m).



(a) t=11.1mm (b) t=15.4mm

(c) t=19.7mm

Figure 4. Deformation cloud atlas of the pipeline collision region after towing anchor impact (L=5m).

Because in this paper it only needs to study the depth of the dents, so the maximum displacement point of the exposed submarine pipeline should be selected from the towing anchor collision area. The maximum displacement δ is obtained by reading the displacement file of the nodes, and the concrete results are shown in Table 2.

Table 2. Results of the towing anchor - pipeline impact model in different wall thickness.

Pipe length L(m)	Pipe wall thickness t (mm)	Maximum displacement δ(mm)	Dent diameter ratio δ/D(%)
5	11.1	11.4	4.17
	15.4	7.2	2.64
	19.7	3.2	1.17

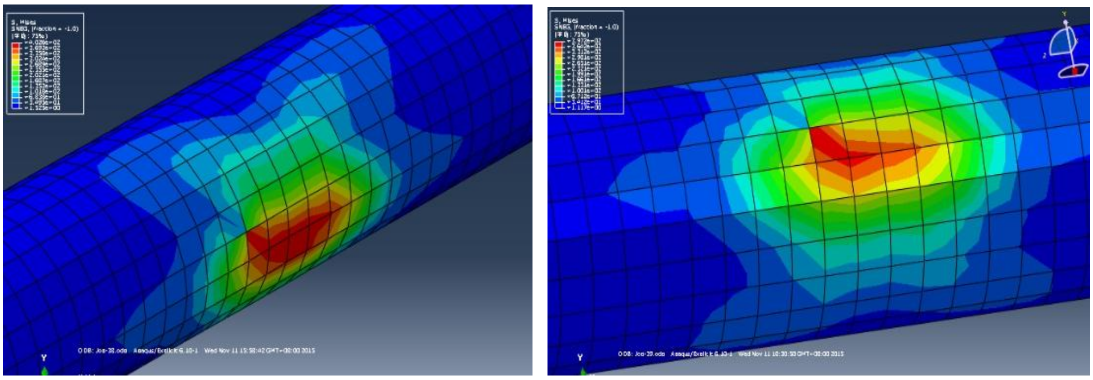
From the above calculation results, it can be found that the dent diameter ratio decreases with the increase of the thickness of the pipe when the impact load remains constant. In other words, the ability of the submarine pipeline to resist impact increases with the increase of the thickness of the pipe wall.

4.3. Study on Relationship between Pipeline Slenderness Ratio and Impact Damage Degree of Towing Anchor

In order to obtain the relationship between the impact damage of the towing anchor and the length of the pipe, it is also needed to get the plastic deformation of different lengths submarine pipelines after collision with the same towing anchor. The length of the submarine pipeline L is 5m, 8m and 10m respectively, the wall thickness t is 11.1mm, and the outer diameter D is 273.1mm.

In the upper section, the ratio of dent depth to outer diameter of the pipeline after the impact with t is 11.1mm and pipe length L is 5m has already been got. The ratio is 4.17%.

The deformation cloud atlas of submarine pipeline with thickness t 11.1mm, length L 8m and 10m is shown by Fig. 5.



(a) L=8m (b) L=10m

Figure 5. Deformation cloud atlas of the pipeline after towing anchor impact (t=11.1mm).

The specific results are shown in Table 3.

Table 3. Results of the towing anchor - pipeline impact model in different slenderness.

Pipe wall thickness t (mm)	Pipe length L(m)	Maximum displacement *δ*(mm)	Dent diameter ratio δ/D(%)
11.1	5	11.4	4.17
	8	10.8	3.95
	10	9.5	3.48

When submarine pipeline is subjected to the lateral impact of towing anchor at low speed, the energy generated will be transformed into local deformation of impact area and overall deformation of the whole pipeline. When the diameter of pipeline remains constant, the larger the slenderness, the smaller the relative stiffness, the smaller the plastic deformation of the pipe after the impact, the more energy absorbed by the whole deformation, the less energy occupied by the local deformation, on this basis, it can be concluded that the impact of the towing anchor on the long distance submarine pipeline is small.

5. Impact Damage Analysis of Dropping Anchor to Submarine Pipeline Based on ABAQUS

5.1. Velocity Calculation before Anchor Landing

First, formula (2) is used to calculate the dropping anchor speed before landing:

$$v_T = \left[\frac{2mg\cdot\left(1-\rho_{water}/\rho_{anchor}\right)}{S_A\cdot\rho_{water}\cdot C_d}\right]^{\frac{1}{2}} \tag{2}$$

Where m is the mass of dropping anchor, 5250kg; S_A is the water retaining area mentioned above, 4.50m^2; g is acceleration due to gravity, 9.8m/s^2; ρ_{anchor} is density of the anchor, 7850kg/m^3; ρ_{water} is density of sea water, 1025kg/m^3; C_d is drag resistance coefficient, 0.8 by referring to the specification rules of DNV-RP-F107.

The former specific values are brought into the formula (2), and the result is as follows:

$$v_T = \left[\frac{2\times5250\times9.8\times\left(1-\frac{1025}{7850}\right)}{4.50\times1025\times0.8}\right]^{\frac{1}{2}} = 4.92\ (\text{m/s})$$

5.2. Establishment and Parameters Setting of Finite Element Model for Dropping Anchor Impact Analysis

The dropping anchor-pipeline impact analysis model is shown in Fig. 6.

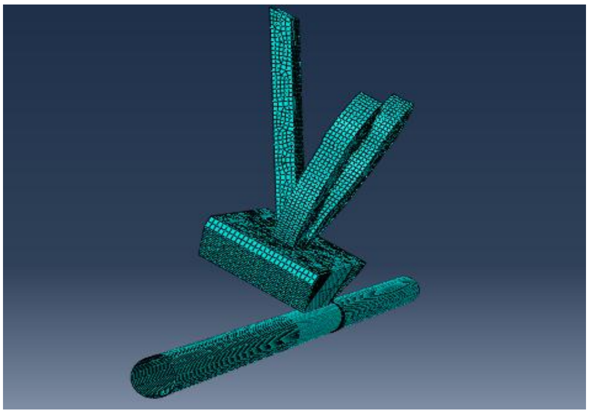
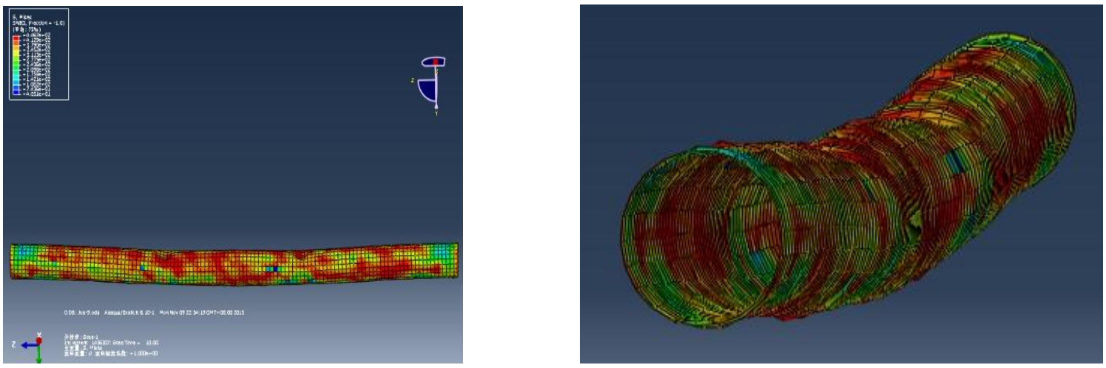


Figure 6. Impact analysis model of dropping anchor to submarine pipeline.

In terms of boundary conditions, both ends of pipeline are rigid fixed and the dropping anchor is only allowed to move in the Y axis. The speed of the anchor movement is simulated by adding a velocity field at its centroid, and 4.92m/s is chosen as the speed of its impact on the submarine pipeline. The other parameters are set up in the same way as above.

5.3. Impact Damage Analysis of Dropping Anchor to Submarine Pipeline

The anchor mass of 5250kg is falling from the sea level, and the pipeline's deformation cloud atlas is shown in Fig. 7 after the pipeline is vertically hit by the dropping anchor.



(a) Global deformation cloud atlas of pipeline (b) Enlarged deformation cloud atlas of pipeline

Figure 7. Deformation cloud atlas of the pipeline after dropping anchor impact (t=11.1mm, L=5m).

The maximum displacement point in the collision area is selected, and the value is read through post-processing. The maximum displacement is 54.81mm and the dent diameter ratio is δ/D =54.81/273.1=20.07%, greater than 20%, the submarine pipeline has been leaked.

6. Comparison of Calculated Values between ABAQUS Numerical Simulation and DNV-RP-F107 Specification Rules

Since the DNV-RP-F107 stipulates that if the maximum depth of the dent is less than 5% of the pipeline diameter, the sea pipe does not need any repair, so the impact energy required for the 5% dent diameter ratio should be firstly calculated.

According to the formula (3), the plastic moment of pipeline m_p can be got:

$$m_p = \frac{1}{4}\sigma_y \cdot t^2 \tag{3}$$

Where σ_y is the yield strength, 530MPa; t is the wall thickness of pipeline, 11.1mm.

The values are brought into the formula (3), and the result of m_p is

$$m_p = \frac{1}{4}\sigma_y \cdot t^2 = \frac{1}{4} \times 530 \times 10^6 \times 11.1^2 \times 10^{-6} = 16325.325(N \cdot m)$$

According to the formula (4), the energy required for the submarine pipeline to cause 5% wall depression, or the absorption energy of the submarine pipeline when the maximum depth of the dent is equal to 5% of the pipeline diameter can be obtained.

$$E = 16 \cdot \left(\frac{2\pi}{9}\right)^{\frac{1}{2}} m_p \left(\frac{D}{t}\right)^{\frac{1}{2}} D \left(\frac{\delta}{D}\right)^{\frac{3}{2}} \tag{4}$$

Where δ is the dent depth, m; D is the outer diameter of pipeline, 273.1mm.

The values are brought into the formula (4), and the result of E is 330458KJ.

The method for calculating the effective impact energy E_E to the submarine pipeline under the condition of mass m of 5250kg towing anchor and speed v of 1.5m/s impacting the submarine pipeline is described in the formula (5).

$$E_E = E_T + E_A = \frac{1}{2}(m + m_a)v^2 \tag{5}$$

Where E_T is kinetic energy of the anchor, KJ; E_A is kinetic energy of the attached water, KJ; m_a is mass of the attached water, kg.

Mass of the attached water ma can be found though formula (6).

$$m_a = m \cdot \frac{\rho_{water}}{\rho_{anchor}} \cdot C_a \tag{6}$$

Where C_a is the additional mass coefficient of anchor, it is 1.0 by referring DNV-RP-F110 specification rules [8].

Therefore, the effective impact energy of the towing anchor E_{ET} is:

$$E_{ET} = \frac{1}{2} \cdot m\left(1 + \frac{\rho_{water}}{\rho_{anchor}} C_a\right) \cdot v^2 = 6677.45(\text{KJ})$$

Therefore, the effective impact energy of the towing anchor E_{ED} is:

$$E_{ED} = \frac{1}{2} \cdot m\left(1 + \frac{\rho_{water}}{\rho_{anchor}} C_a\right) \cdot v_T{}^2 = 71838.66(\text{KJ})$$

According to the above results of the numerical simulation, the dent to diameter ratio of the pipeline is 4.17% and less than 5% when the towing anchor speed v is 1.5m/s, the submarine pipeline can run as usual. But the result of the specification rules calculation is obviously larger than that under the same condition, the dent to diameter ratio can be reached to 7.99% through formula(4), the pipeline is already in medium damage. The impact energy of the dropping anchor at the seabed is 71838.66KJ, the dent to diameter ratio of the pipeline has reached 38.95% and the numerical simulation result is 20.07%, which all embodies the conservatism of the specification rules. The cause of such a large deviation may be due to the standard of the deformation conditions of the submarine pipeline under the impact of the shock load, in the calculation for impact deformation of exposed pipeline, the energy absorption of the impact object and the seabed is not neglected. It is considered in the specification rules that the energy is absorbed only by the pipeline and concrete, so that the pipeline is designed somewhat conservative.

7. Conclusion

To summarize, we can draw the following conclusions:

1) In this paper, the ABAQUS software is used to simulate the impact process of towing anchor and submarine pipelines. The calculation results show that the ability of the pipeline to resist anchorage impact is enhanced with the increase of wall thickness and the slenderness ratio of the pipeline.

2) By comparing the results of the ABAQUS numerical simulation with the calculated values of the DNV-RP-F107, it is found that the specification calculation value is obviously larger. The reason may be that energy absorption of the seabed, the falling objects and the soil above the pipeline is not considered in the specification calculation of the pipe dent. On the other hand, the specification also neglects the influence of nonlinear factors during the impact process, thus causes the results more conservative and set aside a large safety margin.

3) It is suggested that the interaction between submarine pipeline and seabed should be considered in the process of research and standardization in the future, and the coupling effect of various factors should be fully analyzed to get more accurate and economical design results.

Acknowledgments

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