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Based on Anchoring Depth of Penetration of Design Method of Pipeline Buried Depth Research

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Abstract

Submarine pipeline has been widely used in offshore oil and gas transportation due to its advantages of high transportation efficiency, large capacity and being unaffected by weather. Anchoring is one of the main causes of submarine pipeline damage, which may cause impact damage to the pipeline, and then pollute the Marine environment. In this paper, the effect of anchoring penetration depth on buried depth of a liquefied natural gas transportation pipeline is studied based on the actual project. In terms of anchor dropping, the applicable conditions and calculation results of Japanese anchor dropping experiment and ABAQUS finite element method are compared. The empirical prediction method, API 2SK standard prediction method and finite element method were used to study the penetration depth of the anchor. The finite element calculation results were accepted after comparative analysis. Finally, the reasonable buried depth value of engineering pipeline is obtained by combining the existing buried depth design method proposed in this paper. Relevant methods and research results have important guiding significance for the design of submarine pipeline burial depth and pipeline damage assessment of similar projects.

Keywords

Anchoring; Penetration Depth; Finite Element; Pipeline Burial Depth Design.

1. Introduction

With the economic development, the global demand for offshore oil and gas resources is increasing day by day. Submarine pipeline has been widely used in offshore oil and gas transportation due to its advantages of high transportation efficiency, large capacity and being unaffected by weather [1]. However, the increasing frequency of offshore oil and gas drilling, mooring, fishing and other human activities have posed a serious threat to the safety of the submarine pipeline structure. Relevant statistics show that the main reason for pipeline failure in Chinese waters is third-party damage, of which anchoring is the main type, as shown in Figure 1 [2]. Pipelines may be damaged or broken by falling objects, resulting in oil and gas leakage and pollution of the Marine environment [3]. Therefore, buried pipelines are usually used for protection at present.

As for the design and research on the buried depth of submarine pipelines, DNV specification (1996) proposed that at least 0.3m distance should be kept between cross pipelines in the vertical direction, and ditching should be adopted for small diameter pipelines hit by anchor [4]. Federal regulations state that all subsea pipelines in the Gulf of Mexico in water depths of 12 to 200 ft must be buried below the natural seafloor, unless bolting or other protective measures are in place. The ISO 15649 standard recommends a minimum cover thickness of 0.8m for buried pipelines without special protection, but does not specify whether this standard applies to onshore or subsea pipelines.

Wang Fengyun et al. (2011) roughly obtained the buried depth values of pipelines under impact of different anchor weights in different sea areas in China by studying the guiding opinions of relevant domestic and foreign standards on the design of buried depth of submarine pipelines and by investigating and analyzing the causes of submarine pipeline accidents [5]. Zhao Dongyan et al. (2010) pointed out that fishing vessel operations and shipping operations accounted for the main proportion of environmental factors affecting the buried depth of submarine pipelines, and proposed recommended schemes of different buried depths by comparing domestic and foreign laws and regulations on the buried depth of submarine pipelines and combining the actual situation of various sea areas in China [6]. Zhuang Yuan et al. (2013) used physical models to analyze the dropping process of anchors in combination with relevant norms at home and abroad and the research results of domestic scholars, and finally calculated the undersea penetration of anchors [7]. Gao et al. (2016) studied the process of falling anchor penetration into the seabed by means of experimental, numerical and theoretical analysis [8]. Peng Jinsong and Liu Haixiao et al. (2021) proposed a towed anchor theoretical model to analyze anchor motion in layered soil by studying reasonable mechanics and analytical models [9]. Aubeny et al. (2008) proposed a motion trajectory prediction method suitable for saturated soft clay, considering the influence of the shape of anchor plate, the Angle between embedded cable and mud surface and the strength of soil on the trajectory of anchor tow. [10,11]

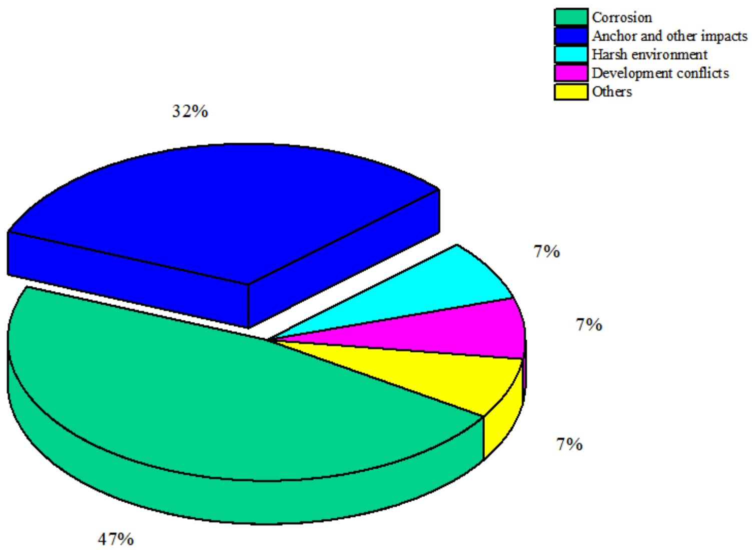

Fig. 1 Causes of submarine pipeline damage in Chinese waters

The above specifications, regulations and research results for the buried depth of pipelines have regional limitations. There is no unified standard for the buried depth of pipelines in the world, and no corresponding regulations have been issued in China. Most scholars still mainly use numerical model research. In this paper, with the help of practical engineering projects and ABAQUS/ Explicit finite element software, the buried depth design method of anchored penetration depth of pipeline is studied. The relevant results and conclusions can provide powerful tools and important references for the buried depth design and pipeline protection of submarine pipeline.

2. Existing burial depth design methods

Under normal circumstances, the design thickness of the buried depth of the pipeline should be considered in combination with the scouring and silting situation of the research sea area, the anchoring depth of the ship type corresponding to each channel and the type of pipeline. Among them, the scouring and silting situation needs to be obtained through seabed geological survey, and the pipeline model can be obtained by engineering needs. In order to avoid damage to the pipeline during anchoring, a reasonable buried thickness should be determined according to the penetration depth of the anchor. The specific designed buried depth thickness is shown in Formula 1. The calculation formula is as follows:

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$$T = max(H, Z) + L + C + D \quad (1)$$

T: design thickness of buried depth of pipeline (m);

H: Penetration depth of anchor drop (m);

Z: penetration depth of tow anchor (m);

L: seabed scour thickness (m);

C: The minimum clearance between the flukes and the pipe should be maintained, which can be set as 0.3m;

D: Total outer diameter of pipe including coating (m).

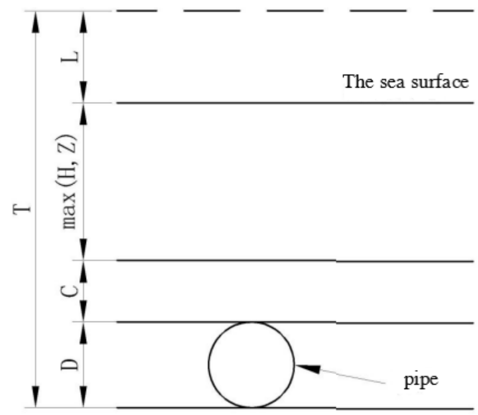

Fig. 2 Schematic diagram of design thickness of buried depth

3. Theoretical research on the depth of anchoring

3.1 Calculation of bottoming speed

The anchoring process of a ship is the process in which the ship anchor drops into the water freely under the action of gravity and then touches and penetrates into the riverbed. The whole process can be modeled in order to accurately calculate the penetration of riverbed after anchoring. Due to the different environment and force of the anchor in each process, it can be divided into three stages: (1) the anchor is thrown from the ship to the water surface for free fall, falling height is h1; (2) The anchor drops from the water surface to the seabed surface at a height of H2; (3) The anchor penetrates into the soil from the seabed surface until it is fixed, falling at a height of H3. According to the different situation of each process, the corresponding model is established. In the whole period of anchor falling movement, vertical downward is taken as positive to establish coordinates, as shown in fig. 3:

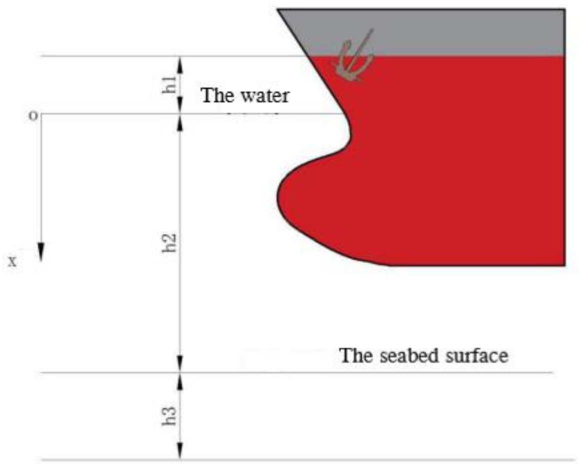

Fig. 3 Schematic diagram of dropping anchor into mud

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The anchor is mainly dragged by gravity G, buoyancy F and water drag F during the second stage of falling, as shown in fig. 4.

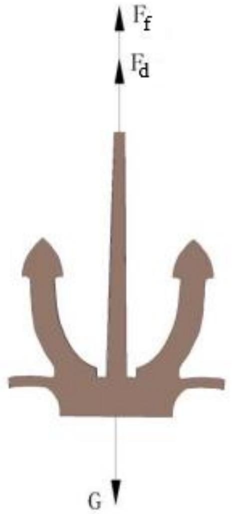

Fig. 4 Stress analysis of anchor in water

If the anchor is released from rest, the initial velocity is zero. When the anchor with dead weight of M is falling freely in seawater, its speed in the falling process can be expressed as:

$$mg-\rho_w Vg-\frac{1}{2}\rho_w C_d A_F v^2=m\frac{dv}{dt} \quad (2)$$

v is the speed of the anchor, in m/s; m is the mass of the anchor, in kg. g is the acceleration of gravity, 9.81m/s^2; A_F is the retaining surface volume of the front face of the anchor, in unit m^2; V is the drainage volume of the anchor, in m^3; ρ_w is the density of seawater, in kg/m^3; Cd is the drag coefficient, which is 1.2.

If the anchor is released at H above the water surface, take the initial value of the equation $v(z=0)=\sqrt{2gH}$, Then, the speed when falling to the water depth z is:

$$v=\left[\left(2gH-\frac{2Vg(\rho_s-\rho_w)}{C_D\rho_w A_F}\right)exp\left(-\frac{\rho_w C_D A_F z}{V\rho_s}\right)+\frac{2Vg(\rho_s-\rho_w)}{C_D\rho_w A_F}\right]^{\frac{1}{2}} \quad (3)$$

ρ_s is the density of anchor, kg/m^3.

According to formula (3) under the same conditions, the calculated bottom touching velocity is compared with the measured data, as shown in Table 1. Comparative analysis of the data in the table shows that the calculated speed is generally larger than the measured speed, and the result is a little conservative.

Table 1. Comparison between anchor bottom speed and measured data

No.	The quality of the anchor(t)	The projection area (m²)	The high in the air (m)	The depth of the water (m)	The measured velocity (m/s)	Computing speed (m/s)	error
1	17.8	3.5	6.3	19.5	8.2	8.47	3.30%
2	17.8	3.5	5	19.5	8	8.43	5.40%
3	16.1	3.3	5	17.2	7.6	8.28	8.90%
4	16.1	3.3	2.5	17.2	7.2	8.19	13.80%
5	16.1	3.3	0	17.2	6.9	8.09	17.20%
6	6.84	1.9	6.5	17	6.9	7.12	3.20%
7	6.84	1.9	3.4	17	6.8	7.07	4.00%
8	6.84	1.9	0	17	6	7.01	16.80%
9	1.26	0.6	1.6	17.7	4.5	5.39	19.80%
10	1.26	0.6	0	17.7	4.5	5.39	19.80%

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3.2 Calculation of anchor depth

The anchoring depth in the process is of great significance to the setting of the buried depth of the submarine pipeline. This section mainly studies the calculation of the anchoring depth by the Japanese anchoring experimental formula and the finite element method.

3.2.1 Japanese anchor throwing experimental formula

Shigeo Nakayama and Ri Qing (1975) studied the calculation method of anchor penetration through a large number of anchor casting tests. Based on a large number of anchor dropping test data, the relationship between anchor penetration depth and anchor hitting energy is studied, and the calculation method of anchor penetration depth based on anchor hitting energy in soft soil and sandy soil is proposed respectively.

The empirical formula proposed by Shigeo Nakayama and Ri Kiyomiya (hereinafter referred to as the "Japanese anchoring test formula") is as follows:

$$\text{In clay: } \Delta H = 0.520 + 0.235E/S \quad (4)$$

$$\text{In sand: } \Delta H = 382 + 0.0348E/S \quad (5)$$

ΔH is the penetration depth, in unit m; E is the kinetic energy of hitting bottom, in unit t·m; S is the projected area of the anchor, in m^2.

Based on the formula of Japanese anchor dropping test, the penetration depth of anchor can be roughly estimated according to the speed of anchor hitting bottom and the type of seabed surface soil.

3.2.2 Prediction of penetration depth by finite element method

In order to adapt to large soil deformation, a coupled Euler-Lagrange (CEL) method was used to establish the ABAQUS finite element numerical analysis model. The model is mainly composed of anchor and soil. The anchor is constrained as rigid body, and the discrete analysis is carried out by C3D10M Lagrange element.EC3D8R Euler element is used to reduce the integral of soil. The contact between anchor and soil adopts the general contact algorithm provided by ABAQUS, which can automatically calculate and update the contact interface. In modeling, when the anchor body is moved to a specified height, the velocity when it reaches the soil surface is the calculated bottom velocity, and all freedom constraints except vertical translational motion are taken into account. The upper surface of soil is free, the lower surface is completely constrained, and the other sides are symmetric constrained. The finite element numerical model is shown in fig. 5. The penetration depth of anchor was calculated by finite element software.

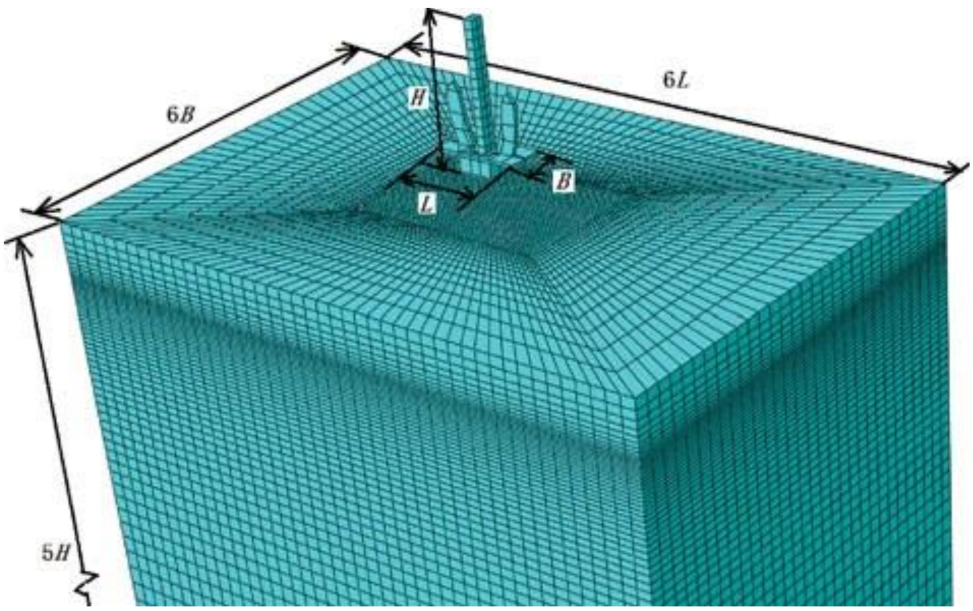

Fig. 5 CEL model of anchor drop

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4. Research on penetration depth of anchor towing process

4.1 Prediction of anchor depth by empirical method

This section mainly calculates the towing depth through the empirical prediction method and API 2SK standard empirical prediction method, and studies and analyzes the influence of different empirical prediction methods on the towing depth.

4.1.1 Empirical prediction method

The empirical prediction method is mainly to get the relatively simplified process of towing anchor penetration through the data results and experience of a large number of practical projects. The function composed of anchor and soil properties can be used to predict anchor penetration depth. After emergency anchoring, the ship sails with anchor towing, and the state of anchor bottom grasping is shown in Fig. 6. Taking Hall anchor as an example, its structural profile is shown in fig. 7:

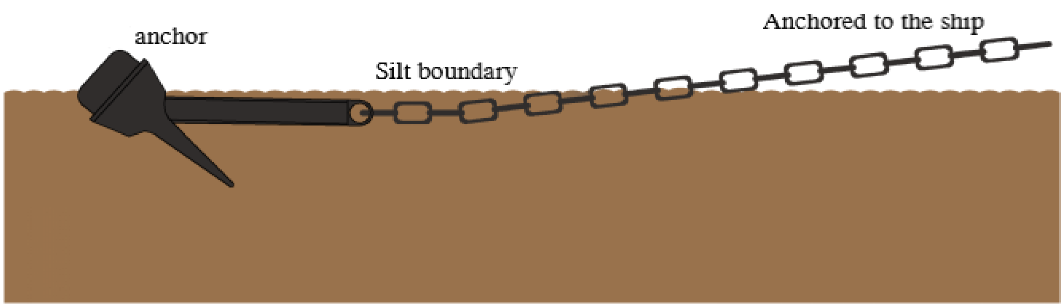

Fig. 6 Schematic diagram of anchor claws sinking into river bed

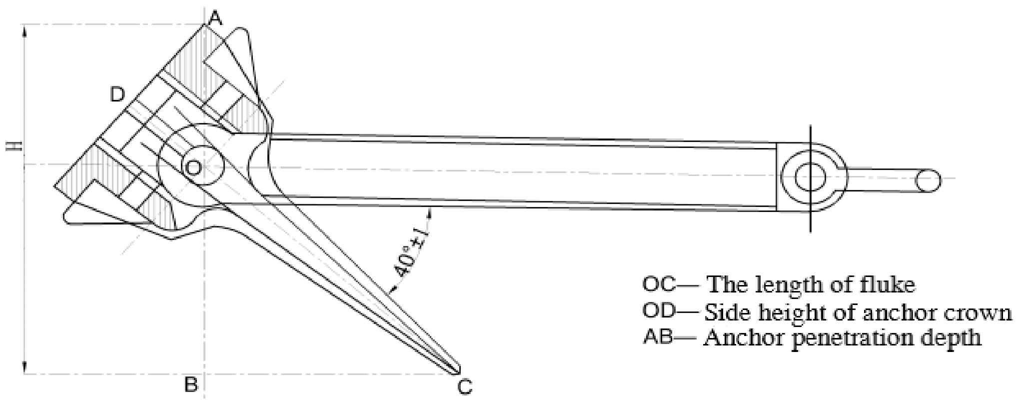

Fig. 7 Schematic diagram of anchor profile structure

Let the length of the anchor fluke be OC=h, the Angle of expansion of the fluke be θ(take the maximum value, θ≈40°), and the thickness of the anchor crown be OD= H1. The embedment depth of anchor is H. After anchoring, the embedment depth of anchor under the condition that all the anchor claws sink into the river bed is:

$$H = \mathrm{OC}\sin\theta = h \cdot \sin\theta \qquad (6)$$

4.1.2 API 2SK specification prediction method

API 2SK specification gives a method for estimating the maximum penetration depth of anchor tip of towed penetration anchor, which is a multiple of the length of anchor plate (fluke). This method is suitable for deep water engineering anchor because of deep mud. The penetration depth of the rodless anchor in sand and hard clay is one time of the length of the anchor claw, and that in silt and soft clay is three times of the length of the anchor claw. For the specific penetration depth of other anchor types, see Fig 8.

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Table D.1—Estimated Maximum Fluke Tip Penetration

Anchor Type	Normalized Fluke Tip Penetration (Fluke Lengths) Sands/Stiff Clays	Mud (e.g., Soft Silts and Clays)
Stockless	1	3*
Moorfast	1	4
Offdrill II		
Boss		
Danforth		
Flipper Delta		
GS (Type 2)	1	$4^1/_2$
LWT		
Stato		
Stevfix		
Stevpris MK III		
Bruce FFTS MK III		
Bruce TS	1	5
Hook		
Stevmud		

*Fixed fluke stockless.

Fig. 8 Relationship between anchor depth and fluke length of different substrates (API RP 2SK)

4.2 Numerical simulation method

In order to meet the practical engineering application, this section uses ABAQUS finite element software to simulate the motion track of ship anchor in soil. In accordance with the finite element model method in Section 3.2, CEL method is also adopted in this section. The model includes three parts: soil, anchor and anchor chain. Due to the symmetry of the model, only a semi-model is needed to reduce the number of meshes and improve the computational efficiency. The deformation of anchor and anchor chain is small and not the focus of the study. The constraint is rigid body, and the mesh is divided by C3D10M Lagrange element.

Due to the advantages of PENALTY function algorithm, such as good iteration, sensitivity to contact stiffness, wide application type and automatic updating detection at contact points, this section adopts PENALTY function algorithm to define model interaction, and the friction coefficient is 0.4.In the process of anchor towing, the reverse catenary shape of anchor chain has a great influence on the trajectory of anchor movement, so this section simplifies the anchor chain by building equivalent columns with exactly the same length, weight and bearing capacity. LINK unit is set to connect the rigid cylindrical segment, as shown in fig. 9.

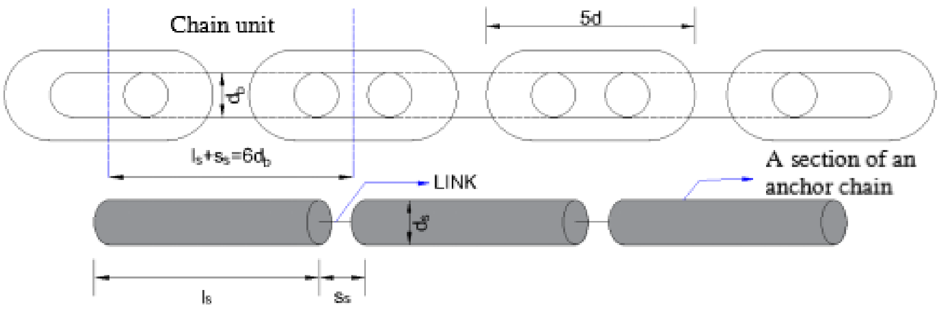

Fig. 9 Schematic diagram of LINK unit

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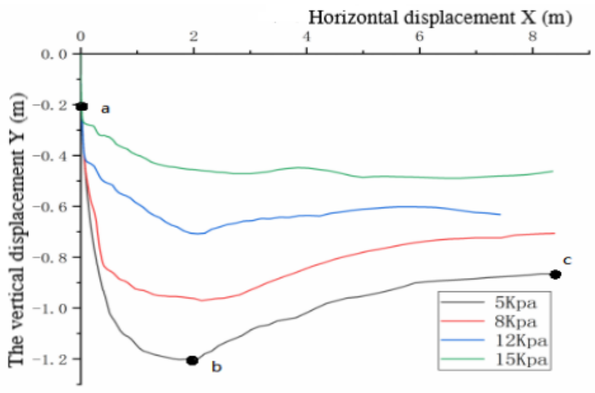
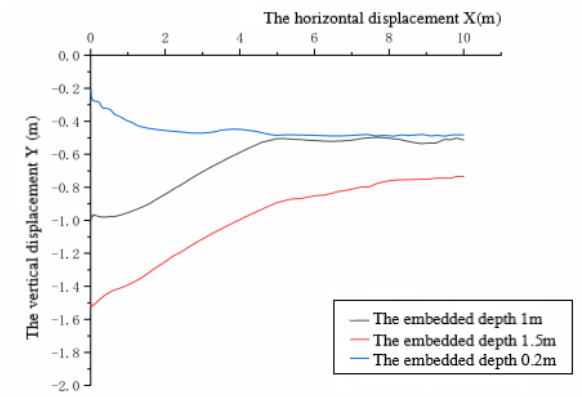
In the process of simulating anchor track in this chapter, it is assumed that anchor and anchor chain only move in the X-Z plane, and the motion of anchor and anchor chain in the Y direction and rotation around the X and Z axes should be fixed. Other boundary conditions are set in accordance with the finite element model in Section 3.2.

4.3 Study on towing motion mechanism

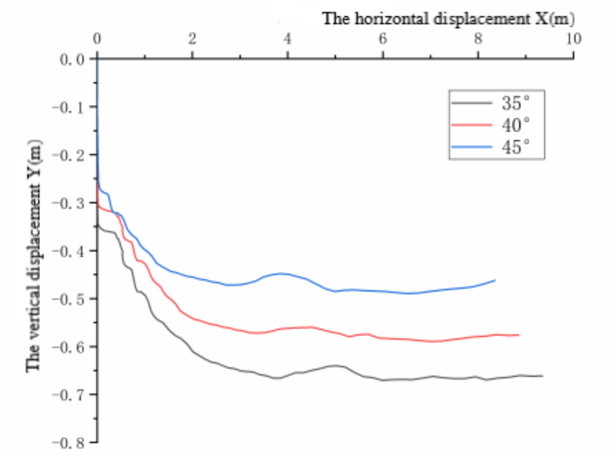
There are many factors that affect the towing trajectory. This section mainly studies the towing trajectory from the undrained shear strength of soil, the initial embedding depth of anchor and the pivot Angle of anchor, and further analyzes the motion mechanism of anchor in the process of towing. In this section, the trajectory of anchor towing under 4 soil conditions of 5kPa, 8kPa, 12kPa and 15kPa are studied respectively. Under the condition of undrained shear strength of 5kPa, the anchor was anchored on the trawl track with initial mud penetration depth of 0.2m, 1m and 1.5m. When the undrained shear strength of soil is 5kPa and the initial embedding depth of anchor is 0m, the finite element drag trajectory of anchor is studied with pivot angles of anchor claws of 35°, 40° and 45°, respectively. The specific track of anchor towing is shown in Fig. 10.



(a)



(b)



(c)

Fig. 10 (a) Tow trajectory of different soils; (b) towing trajectory at different initial embedding depths; (c) Anchor towing track under different pivot angles of anchor flukes

As shown in Fig. 10 (a), the initial embedding depth and movement trend of anchors in different soils are roughly the same. They all move into the mud first, then move upward when reaching the maximum embedding depth, and finally move horizontally at a certain depth. From Fig. 10 (b), the influence on different initial embedded depth of clubbing tracks, and do not fully embedded in the soil anchor will further into the mud, after reaching a depth horizontal motion, and to fully embedded in the soil anchor, its trajectory is roughly same, but with the increase of initial depth of anchor the

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end of the day, the depth of the horizontal motion increases. The results in Fig. 10 (c) show that with the increase of pivot Angle, the towing track depth decreases.

5. Engineering application and discussion

Mentioned in section in the paper this section, starting from the engineering practice, considering the depth of each section, geology, navigation conditions, such as by Japan cast anchor experiment formula and finite element method (fem) analysis of anchor the result of the penetration depth, using clubbing experience prediction method and the finite element method analysis the result of the penetration depth, and the calculation results were analyzed.

5.1 Analysis of the result of anchor penetration depth

In this section, the Japanese empirical formula of anchor dropping test and the finite element method combined with the typical point 1 of this project are selected to analyze the penetration depth of anchor dropping. The advantages and disadvantages of each method and the applicability of this study are shown in Table 2:

Table 2. Analysis of advantages and disadvantages and applicability of each method

method	Advantage	disadvantage	Applicability of this paper
Japanese empirical formula for anchor casting test	Simple and easy to operate; Consider the impact energy.	Soil mechanical parameters, water depth, ship type and other factors cannot be considered	The applicability is poor and the predicted value is large
finite element method	In addition to the advantages of theoretical analysis, it can more truly reflect the process of anchor-soil interaction, and the results are more comprehensive and real.	A longer time	application

As can be seen from the above table, the finite element method is relatively more suitable for the analysis of emergency anchoring penetration depth in this paper. The formula of anchor casting test in Japan only divides soil into two types, so obviously the predicted value deviation will be large, especially for the substrate with poor bearing capacity such as silt and silt.

Table 3 lists the calculation results based on the two methods. The analysis shows that the finite element method is more suitable for the penetration depth analysis in this paper. The penetration depth in this paper was finally analyzed by the finite element method. The deepest penetration was the emergency anchoring condition of 70,000GT ro-ro ship at point 1, and the maximum penetration depth was 1.9m.

Table 3. Calculation results of emergency anchoring penetration depth

point	ship type	The anchor type	Anchor weight/kg	depth of water/m	The bottom of the speedm/s	Penetration depth/m	
						finite element	Japan cast anchor
1	20000t	Hall	6000	7.83	6.82	1.36	2.61
	50000t	Hall	8300		7.36	1.74	3.35
	70000GTro-ro	AC-14	9675		7.46	1.9	3.3

5.2 Analysis of the penetration depth of anchor towing

In this section, the empirical method, API 2SK standard method and finite element method are used to calculate the penetration depth of towing anchor combined with navigable ship types in typical engineering areas. The analysis results show that the anchor with large grasping force of 9675kg AC-14 is larger than the other two anchors in geometric size, and the depth of towing anchor is significantly deeper. See Table 4 for a summary of the depth of towing into mud obtained by various methods.

Table 4. Penetration depth of tow anchor by different methods

prediction technique	Depth of drag penetration(m)
empirical method	1.56
API 2SKspecification method	2.34
finite element method	1.62

Due to the poor applicability and large error of the empirical method for this project, API 2SK method is mainly applicable to deep-water Marine engineering anchors. Therefore, the project adopts the results of dragging anchor depth predicted by finite element method.

5.3 Pipeline buried depth calculation

It can be seen from the above results that the results calculated by the finite element method are taken as the trusted value of the project in this paper, wherein the maximum penetration depth of anchor drop is 1.9m, and the maximum penetration depth of anchor drag is 1.62m. According to the engineering seabed evolution report, the scouring and silting values of different routing segments after 40 years are obtained. Among them, the maximum scouring depth of general pipeline seabed is 1.97m, and the maximum scouring depth of harbor main channel intersection is 1.66m. According to formula 1, the design values of the submarine pipeline buried depth at the intersection of general pipeline and main channel are 5.2m and 4.9m respectively.

6. Conclusion

In this paper, the finite element embedding depth design method under anchoring condition is obtained by comparing the anchoring depth results calculated by empirical method and finite element method based on the engineering practice and referring to the relevant codes and regulations for pipeline laying and the research results of scholars at home and abroad. This method can further reduce the damage of anchoring pipeline and put forward a valuable scheme for the design of buried depth of pipeline in practical engineering.

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