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Numerical Simulation of Submarine Pipeline Self-Buried on Sediment Seabed

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Abstract

With the process of the exploitation of the petroleum resources inland, people begin to focus on petroleum buried in the subsea. Now about 100 countries around the world are taking steps to prospecting petroleum offshore, in the meantime, the submarine pipeline plays the role of important tool to transport crude oil, it is not only convenient but also be able to transport largely continuously. In order to guarantee the submarine pipeline get rid of waves, tide, ocean current and other oceanic hydrometric elements and keep the balance on location, usually we should put it buried. The common approach is to dig it and backfill then. In the process, the trencher is necessary.

To save more extra expense, people take the measure to load a setting above the bottom hole flow bean which is similar to the fins[1] to realize the burial of the pipeline itself. Here we adopt the bottom hole flow bean technology that China Hangzhou Bay submarine pipeline has utilized to reach the aim of the burial of the pipeline as the realistic basis, what is more, we use the numerical simulation software, FLUENT, aims at the submarine pipeline self-buried on sediment seabed. By the ways of analyzing the modality of the scour hole when there exists bottom hole flow bean or not, the pressure coefficient of the surface of the pipeline, the situation of the flow below the pipeline, to tell the influence of the bottom hole flow bean to the submarine pipeline self-buried. Based on it, we have simulated the process of the submarine pipeline self-buried. Through the simulation we can get to know the erosion and deposition situation of the washings around in the process of falling down so as to show the self-buried of the pipeline which is under the influence of bottom hole flow bean.

Key words: Bottom hole flow bean; Submarine pipeline; FLUENT; Sediment seabed; Self-buried

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INTRODUCTION

Thanks to the continuous exploitation of offshore oil and gas, submarine oil and gas pipeline as the most direct ways for transporting has already become the lifeline of offshore oil and gas field[2]. As an ocean engineering technology which is risen with the exploitation of marine oil and gas resources, the paving of submarine pipeline is featured with high investment and risk so compared the paving of land pipeline it will cost more. Usually the pipeline paved in the seabed should be buried which is to get rid of the risk because of the waves and current of losing balance on location for the exposed pipeline; on the other hand, the measure will protect the pipeline away from harm when it get across of anchorage ground, fairway and other fishery activity area. Besides according to the requirement that the local government has declared in order to protect the pipeline from damage by the sleet or the erosion in the landed section also the pipeline should be buried. Moreover, the burial of the pipeline also can keep itself warm[3]. The traditional burial way for submarine pipeline are pre-ditch and later ditch. All of the two ways need the underwater ditcher while different kinds of ditchers are expensive. In order to save more expense, domestic and overseas take the new approach of loading bottom hole flow bean to reach the submarine pipeline self-buried. In China, the paving of submarine pipeline in Hangzhou bay has been put into application firstly and reap ideal effects. As a result, we take the paving of submarine pipeline in Hangzhou bay as the realistic basis and utilize the software of FLUENT to take the numerical simulation to the pipeline without bottom hole flow bean to simulated the situation to the erosion and deposition of the nearby silt seabed and simulate the process of submarine pipeline self-buried. Through analyzing the data of the configuration of erosion pit which near the pipeline, the pressure coefficient of the pipeline surface and the water velocity under the pipeline to prove that the loading of bottom hole flow bean will promote the submarine pipeline self-buried. By means of the numerical simulation in the process of submarine pipeline self-buried we can find the variation of the erosion and deposition of nearby seabed. Also it can tell the commotion effort that the bottom hole flow bean to the nearby flow.

1. TURBULENCE MODEL

We use the Euler model that is in the software of FLUENT to take the simulation of the sediment seabed near the submarine pipeline of which includes water phase and slime phase. The density for water is $\rho = 998.2$ kg/m^3, coefficient of viscosity is $\mu = 0.001003$ kg/m·s, the slime granule is oceanic sand and it's specific gravity is 2.68. The median grain diameter is $d_{50} = 0.5$ mm. The viscosity is 10 kg/m·s. In the process of simulation wen assume the sediment load is made up of solid phase s and fluid phase. They are independent in mutual and in mutual action interaction to form continuous flow. We use α ($0 \le \alpha \le 1$) to stand for the volume fraction and both they agree with law of conservation of mass and law of conservation of momentum.

1.1 The Turbulence Model for Fluid Phase

We use standard k - ε model and the additive term of different phase turbulence momentum transfer to derive the turbulence prediction for continuous phase. The Reynolds stress tensor for continuous phase f is shown in the following formula:

$$\bar{\bar{\tau}}_f = -\frac{2}{3}\left(\rho_f k_f + \rho_f \mu_{t,f} \nabla \cdot \vec{U}_f\right)\bar{I} + \rho_f \mu_{t,f}\left(\nabla \vec{U}_f + \nabla \vec{U}_f^T\right). \quad (1)$$

In the formula: $\vec{U}_f$ is the weighted velocity. $\mu_{t,f}$ is turbulence.

$$\mu_{t,f} = \rho_f C_\mu \frac{k_f^2}{\varepsilon_f}. \quad (2)$$

We define the characteristic time for Current-carrying turbulent vortex is

$$\tau_{t,f} = \frac{3}{2} C_\mu \frac{k_f}{\varepsilon_f}. \quad (3)$$

In the formula: ε_f is coefficient of losses. The $C_\mu = 0.09$.

We use the following transport equation to predict the turbulence kinetic energy k_f and the coefficient of losses ε_f[4].

$$\frac{\partial}{\partial t}\left(\alpha_f \rho_f k_f\right) + \nabla \cdot \left(\alpha_f \rho_f \vec{U}_f k_f\right) = \nabla \cdot \left(\alpha_f \frac{\mu_{t,f}}{\sigma_k} \nabla k_f\right) + \alpha_f G_{k,f} - \alpha_f \rho_f \varepsilon_f + \alpha_f \rho_f \prod_{k_f}. \quad (4)$$

$$\frac{\partial}{\partial t}\left(\alpha_f \rho_f \varepsilon_f\right) + \nabla \cdot \left(\alpha_f \rho_f \vec{U}_f \varepsilon_f\right) = \nabla \cdot \left(\alpha_f \frac{\mu_{t,f}}{\sigma_\varepsilon} \nabla \varepsilon_f\right) + \alpha_f \frac{\varepsilon_f}{k_f}\left(C_{1\varepsilon} G_{k,f} - C_{2\varepsilon} \rho_f \varepsilon_f\right) + \alpha_f \rho_f \prod_{\varepsilon_f}. \quad (5)$$

In the formula: $\prod_{kf}$ and $\prod_{\varepsilon f}$ means the influence of dispersion phase s to the continuous phase f.

$$\prod_{k_f} = \frac{K_{fs}}{\alpha_f \rho_f}\left(k_{sf} - 2k_f + \vec{\upsilon}_{sf} \cdot \vec{\upsilon}_{dr}\right). \quad (6)$$

$$\prod_{\varepsilon_f} = C_{3\varepsilon} \frac{\varepsilon_f}{k_f} \prod_{k_f}. \quad (7)$$

$\vec{v}_{dr}$ is drift velocity $\vec{\upsilon}_{dr} = -D_{t,sf}\left(\frac{1}{\sigma_{sf}\alpha_s}\nabla\alpha_s - \frac{1}{\sigma_{sf}\alpha_f}\nabla\alpha_f\right)$. (8)

$\vec{v}_{sf}$ is relative velocity. $D_{t,sf}$ is the turbulence dissipation factor. $\sigma_{sf} = 0.75$. k_{sf} is the velocity covariance of continual phase f and dispersion phase s. $G_{k,f}$ stand for the formation of turbulence kinetic energy. $C_{1\varepsilon} = 1.44$, $C_{2\varepsilon} = 1.92$, $C_{3\varepsilon} = 1.2$, $C_k = 1.0$, $C_\varepsilon = 1.3$.

1.2 The Turbulence Model for Solid Phase

We apply the relationship of Tchen-theory to the turbulence prediction of dispersion phase and the physical quantity which characterize motion like time and length are used to estimate propagation factor, correlation function and the turbulence kinetic energy of dispersion phase. The parameter which is connected with the iterance influence of the dispersion phase for the relaxation time of characteristic particle is defined as the following formula:

$$\tau_{F,sf} = \alpha_s \rho_f K_{sf}^{-1}\left(\frac{\rho_s}{\rho_f} + C_V\right). \quad (9)$$

In the formula: $C_V = 0.5$ is the mass coefficient.

Lagrangian proportional integral differential is calculated along with the particle orbit which is influenced mainly by the crosswise orbit. We define it as:

$$\tau_{t,sf} = \tau_{t,f}\left[1 + C_\beta \xi^2\right]^{-\frac{1}{2}}. \quad (10)$$

In the formula: $\xi = \left|\vec{V}_r\right| \Big/ \sqrt{\frac{2}{3}k_f}$, $\tau_{t,f} = \frac{3}{2}C_\mu \frac{k_f}{\varepsilon_f}$, $\vec{v}_r$

is the general average of the relative velocity between particle and the flow field nearby. $C_\beta = 1.8\text{-}1.35\cos^2\theta$, θ is the included angle between mean particle velocity and mean relative velocity. We mark the characteristic time ratio as:

$$\eta_{sf} = \frac{\tau_{t,sf}}{\tau_{F,sf}}. \quad (11)$$

According to Simonin the form of turbulence measurement k_s of dispersion phase will be such form in the software of FLUENT:

$$k_s = k_f\left(\frac{b^2+\eta_{sf}}{1+\eta_{sf}}\right). \quad (12)$$

And the solid phase eddy viscosity will be:

$$D_s = D_{t,sf} + \left(\frac{2}{3}k_s - b\frac{1}{3}k_{sf}\right)\tau_{F,sf}. \quad (13)$$

Where $$D_s = D_{t,sf} + \left(\frac{2}{3}k_s - b\frac{1}{3}k_{sf}\right)\tau_{F,sf}. \quad (14)$$

In the formula, k_{sf} is the covariance of continuous phase.

1.3 The Transportation Equation of the Temperature to Particle

The particle temperature of the solid phase is in direct proportion to its kinetic energy when it is in random motion. We can inform such transportation equation:

$$\frac{3}{2}\left[\frac{\partial}{\partial t}(\rho_s\alpha_s\Theta_s)+\nabla\cdot(\rho_s\alpha_s\vec{\upsilon}_s\Theta_s)\right]=\left(-P_s\bar{\bar{I}}+\bar{\bar{\tau}}_s\right):\nabla\vec{\upsilon}_s+\nabla\cdot(k_{\Theta s}\nabla\Theta_s)-\gamma\Theta_s+\phi_{fs}. \quad (15)$$

In the formula: $(-P_s\bar{\bar{I}}+\bar{\bar{\tau}}_s)$: $\nabla\vec{v}_s$ is the energy of solid stress tensor. $k_{\Theta s}$ is the coefficient of proliferation.

$$k_{\Theta s} = \frac{15d_s\rho_s\alpha_s\sqrt{\Theta_s\pi}}{4(41-33\eta)}\left[1+\frac{12}{5}\eta^2(4\eta-3)\alpha_s g_{0,ss} + \frac{16}{15\pi}(41-33\eta)\eta\alpha_s g_{0,ss}\right]. \quad (16)$$

$k_{\Theta s}\nabla\Theta_s$ is the energy dispersal and $\eta = \frac{1}{2}(1+e_{ss})$

$$\gamma\Theta_s = \frac{12(1-e_{ss}^2)}{d_s\sqrt{\pi}}\rho_s\alpha_s^2\Theta_s^{\frac{3}{2}}. \quad (17)$$

$\gamma\Theta_s$ is the collision deterioration of energy which will stand for the energy deterioration efficiency formed in the process of the collision of solid phase inner collision.

$$\phi_{fs} = -3K_{fs}\Theta_s. \quad (18)$$

ϕ_{fs} is the transportation of random fluctuating kinetic energy thanks to the change of particle movement velocity from s solid phase to f liquid phase to generate.

2. NUMERICAL SIMULATION OF SUBMARINE PIPELINE SELF-BURIED ON SEDIMENT SEABED

2.1 Building the Model

The model having been built is based on the submarine pipeline of Hangzhou bay. We use the realistic submarine pipeline when taking the step of numerical simulation. The outside diameter of the pipeline is D = 791 mm and the internal diameter of the pipeline is $\phi 711\times 14.3$ mm. The thickness of the cement concrete surrounded the ectooecium is 40 mm. Here are the connected parameter in the tabulation one.

Table 1
The Partial Designing Parameter of the Submarine Pipeline in the Bay of Hangzhou[5]

Designing parameter	Number
Diameter (mm)	791
Product density (kg/m^2)	856
Designing press (MPa)	7.3
Pipeline wall thickness (mm)	14.3
Material model number	API 5L X60
Thickness of the cement concrete outer (mm)	40
Density of the cement concrete outer (kg/m^3)	3,044

The simulation is based on the erosion of the silt seabed near the pipeline which has loaded the bottom hole flow bean or not. We only consider the element of ocean current and it is assumed as uniform flow[6]. We set the velocity of flow is 1 m/s and 2 m/s as the comparison. The calculation area is chosen about 20 m × 20 m where the thickness of silt is 2 m. We assign the top of the model is symmetry boundary and the surface of the pipeline besides the right-and-left lower boundary are the wall. The right edge is the outlet of pressure. Here is the specific model followed.

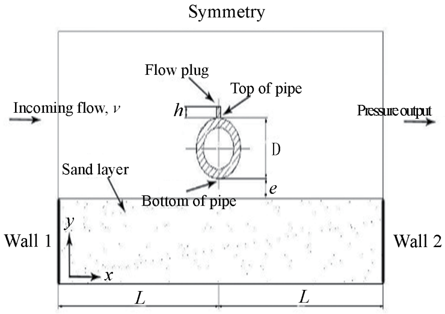


Figure 1
Modeling Diagram

Not only the parameter of velocity of flow can change but also the height of the bottom hole flow bean *h* and the aperture width of seabed *e*. As a consequent, we can simulate the nine operating condition when loaded the bottom hole flow bean and the three operating condition where the pipeline unloaded the bottom hole flow bean. The result is shown as the Table 2. From the comparison, we can find the bottom hole flow bean will promote the submarine pipeline self-buried.

Table 2
Simulation Operating Condition of Silt Seabed Pipeline

Load the bottom hole flow bean		Unload the bottom hole flow bean
	v = 1 m/s, 2 m/s	
$h = 0.125D$	$e = D/8$	$e = D/8$
$h = 0.25D$	$e = D/4$	$e = D/4$
$h = 0.375D$	$e = D$	$e = D$

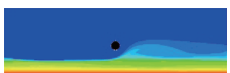
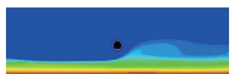
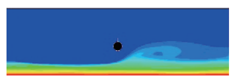
In the table, *v* is the current velocity of flow; *h* is the height of the bottom hole flow bean; *D* is the outside diameter of pipeline, *e* is the width between pipeline and seabed.

2.2 The Analyzing of the Consequent

2.2.1 The Modality of the Scour Hole Near the Pipeline

We assume the original gap width between seabed and pipeline is $D/4$ and then take the simulation of the eroded influence of the flow velocity to the silt near the pipeline. The flow velocity respectively is 1 m/s and 2 m/s meanwhile we take the simulation of the silt erosion form where there exists different heights of the bottom hole flow bean and they are $h = 0.125D$, $h = 0.25D$ and $h = 0.375D$ to tell the influence of the height of the bottom hole flow bean to the pipeline self-buried. The consequent is shown in the following picture.

Table 3
Modality of the Scour Hole Near the Pipeline

			
v = 1 m/s, h = 0	v = 1 m/s, $h = 0.125D$	v = 1 m/s, h = 0. 25D	v = 1 m/s, $h = 0.375D$
			
v = 2 m/s, h = 0	v = 2 m/s, $h = 0.125D$	v = 2 m/s, h = 0. 25D	v = 2 m/s, $h = 0.375D$

From the results shown in the table above we can inform that: The scour hole distributes nearly the pipeline as a result the existence of pipeline will never ruin the stability of the whole seabed. Compared with the pipeline without loading the bottom hole flow bean, the loading of the bottom hole flow bean will lead to the scour hole enlarge the square and the depth will increase obviously[7]. If the height of the bottom hole flow has increased ,the watercourse distributing behind the pipeline will enhance and carry over some silt which will promote the backfill of the silt near the pipeline an then accelerate the pipeline self-buried. While when the flow velocity increase, the time to the pipeline self-buried will be shorten.

2.2.2 The Pressure Coefficient of the Surface of the Pipeline

We simulate the situations of the pressure coefficient of the surface of the pipeline when the heights of the bottom hole flow bean are respectively $h = 0$, $h = 0.125D$, $h = 0.25D$ and $h = 0.375D$. We concluded the results when the width of the gap are respectively $D/8$,$D/4$,and D. The data result is shown in the following Figure 2.

Having analyzed the results we can find that: The distribution of pressure is anisomerous and there exists the pressure difference which lead to the form of drag force. The loading of the bottom hole flow bean makes the drag force bigger and then up to erosion. There exists pressure difference between the top and the bottom of the pipeline which will form the vertical lift force. The loading of the bottom hole flow bean will decrease the factor of lift force which is beneficial to self-buried.

When the widths of the gaps increase, the surface press of the hinderland to the pipeline will increase obviously and there is no great difference compared with the one ahead the pipeline. Even the phoneme of balance will appear when $e = D$. The pressure coefficient is similar on the whole which means the flow velocities are very nearly the same.

2.2.3 The Flow Velocity Under the Pipeline

Still we assume the flow velocities respectively are v = 1 m/s and v = 2 m/s and we output the data of the flow velocity which is under the pipeline when the gap width are $e = D/8$, $e = D/4$, and $e = D$ We have concluded the following result shown as the Figure 3.

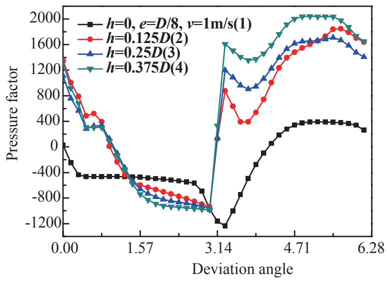


Figure 2(*a*) $e = D/8$, v = 1m/s

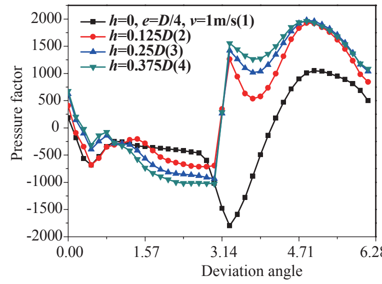


Figure 2(*b*) $e = D/4$, v = 1m/s

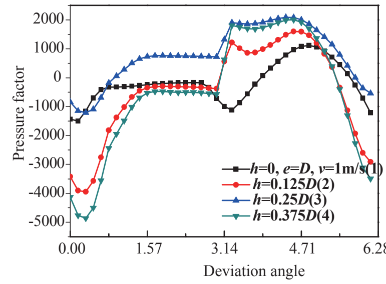


Figure 2(*c*) $e = D$, v = 1m/s

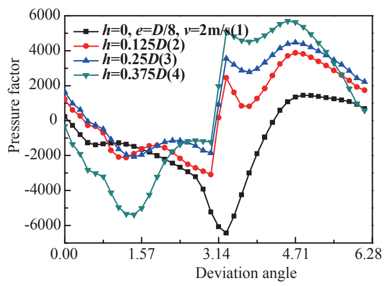


Figure 2(*d*) $e = D/8$, v = 2m/s

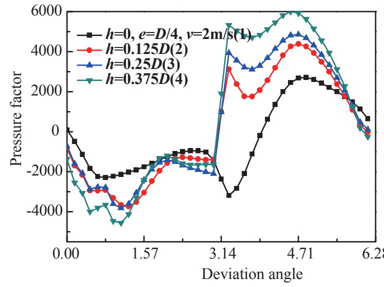


Figure 2(*e*) $e = D/4$, v = 2m/s

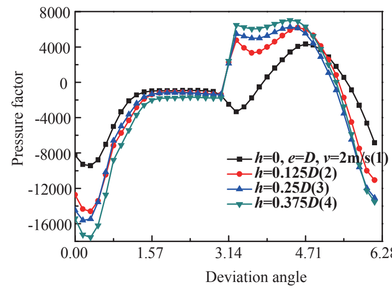


Figure 2(*f*) $e = D$, v = 2m/s

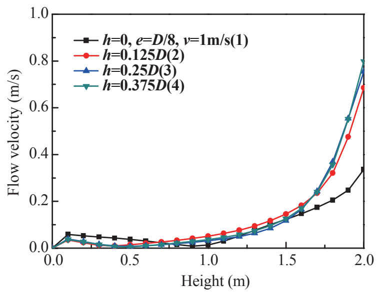


Figure 3(*a*) $e = D/8$, v = 1 m/s

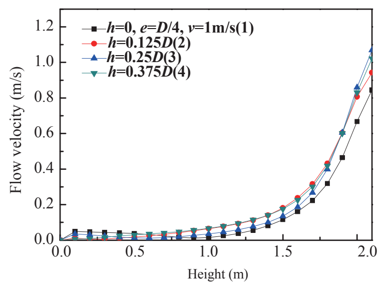


Figure 3(*b*) $e = D/4$, v = 1 m/s

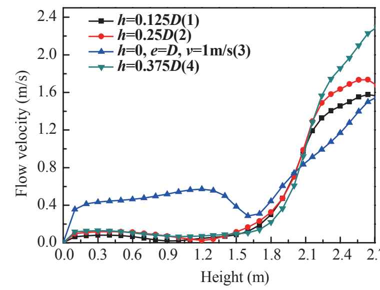


Figure 3(*c*) $e = D$, v = 1 m/s

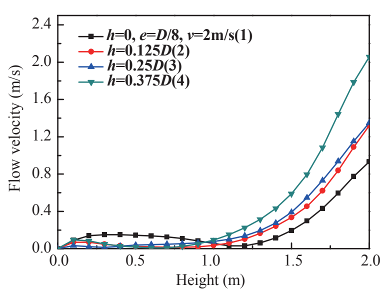


Figure 3(*d*) $e = D/8$, v = 2 m/s

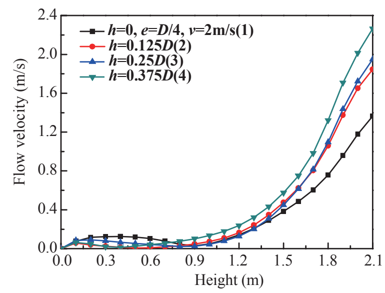


Figure 3(*e*) $e = D/4$, v = 2 m/s

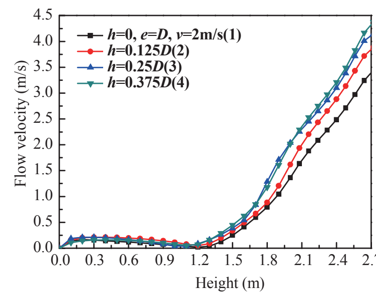


Figure 3(*f*) $e = D$, v = 2 m/s

From the tables we can know that: When the flow velocity is $v = 1m/s$, if the gap width is relatively small the increasing of the height of the bottom hole flow bean promote the flow velocity little. With the increasing of the gap width, the promotion will be much obvious. The phoneme means when the pipeline appear larger hang in the air, with the increasing of the height of the bottom hole flow bean, it will regulate the flow velocity to promote the pipeline self-buried which should not be ignored now. When the flow velocity is $v = 2$ *m/s*, if the gap width is relatively small. The increasing of the height of the bottom hole flow bean will great promote the increasing of the flow velocity. Though the gap width increase, the promotion is not that obvious. The phenomenon means when the flow velocity is relatively high, in the stage of the beginning of erosion, the increasing of the height of the bottom hole flow bean will promote the increasing of the flow velocity. While the depth of the scour pit become increase, the influence of the increasing of the height of the bottom hole flow bean to erosion become decreased. When it never be the key element. However, compared the situation where there is no the bottom hole flow bean, it still promote the erosion.

3. THE NUMERICAL SIMULATION IN THE PROCESS OF PIPELINE SELF-BURIED

We take the simulation of the process of the pipeline self-buried. We assume the gap width between the pipeline and the seabed is zero which equal to the situation of the bare pipeline self-buried which cling to the seabed. In order to be much continent to watch the erosion and deposition of the seabed near the silt in the process of pipeline self-buried. We assume the sinking speed to be a constant. Firstly we assign the sinking speed of the pipeline is 0.0001 m/s which equal to rigid body so we utilize the specific function in the software of FLUENT which is used to defined rigid body movement to take the simulation of the sinking movement of the pipeline. The function is DEFINE_CG_MOTION. Here is the programming language which is used to assign the pipeline speed.

```
#include "udf.h"
DEFINE_CG_MOTION(piston,dt,vel,omega,time,dtime)
{
Thread *t;
face_t f;
real NV_VEC(A);
/* reset velocities */
NV_S(vel, =, 0.0);
NV_S(omega, =, 0.0);
if (!Data_Valid_P( ))
return;
t = DT_THREAD(dt);
/* set y-component of velocity */
vel[1] = -0.0001;
}
```

We lead the programming language to the software of FLUENT. Through translate and compile we endow the function of DEFINE_CG_MOTION with movement boundary and set the mesh parameter. We use the Smoothing and Remeshing in the list of Mesh Methods to adopt the mesh. In order to avoid appearing negative volume we chose the step of iteration time as 0.0001 s. Here is the phase distribution figure as followed:

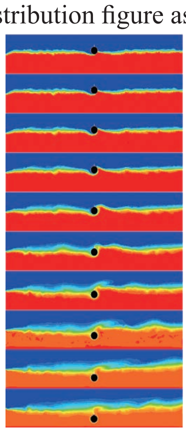


Figure 4
The Phase Distribution Picture in the Process of Self-Buried

So far we can conclude: The water erosion will leave the seabed behind the pipeline to form scour hole. The eroded silt will form siltation behind the pipeline while there will form trench ahead the pipeline. Thanks to the self-weight of the pipeline it will sink generally and the silt piled up behind the pipeline will gather until backfilling the surface of the pipeline. When the pipeline sink to a certain depth, the silt ahead the pipeline and behind the pipeline will mix and bury the pipeline into the sand. With the influence of water flow the silt covered will distribute on average.

CONCLUSION

In order to research influence of the loading of the bottom hole flow bean to the silt erosion of the submarine pipeline the article has simulated the situations where load the bottom hole flow bean or not. With the two operational modes we have analyzed two kinds of flow velocity, three kinds of heights of the bottom hole flow bean and three kinds of gap widths. In the above conditions, we analyzed the erosion to silt seabed near the submarine pipeline. Through the analyzing the conformation scour hole of the silt seabed、the pressure coefficient of the surface of the pipeline and the water flow velocity under the pipeline we have made such conclusion:

(a) The article has simulate the silt erosion and deposition situations near the pipeline when $v = 1$ m/s and $v = 2$ m/s. Through the analyzing we can find that the flow velocity is higher, the silt erosion to the pipeline nearby will be much fiercer and it will be much beneficial to the pipeline self-buried. This means the maritime space where the tidal current is at a high flow velocity like the bay of Hangzhou, it is possible to load the bottom hole flow bean on the pipeline to realize the goal of pipeline self-buried.

(b) Comparing and analyzing the simulation results of the pressure coefficient to the surface of the pipeline when $h = 0$, $h = 0.125D$, $h = 0.25D$, $h = 0.375D$ we can conclude that the loading of the bottom hole flow bean will enlarge the pressure difference between the front and the back while the drag force will be bigger which lead to the pressure difference reduce so as to shorten the pipeline self-buried time. With the increasing of the height of the bottom hole flow bean, the promotion efforts will be much obvious.

(c) Through the flow under the pipeline velocity consequents we have gotten the simulation results of the pressure coefficient to the surface of the pipeline when $e = D/8$, $e = D/4$ and $e = D$ we can conclude that: When the flow velocity is 1 m/s and the gap width is quiet large, the height increasing of the bottom hole flow bean great influence the flow velocity. When the pipeline is pending, the higher the bottom hole flow bean, the much beneficial to pipeline self-buried. When the flow velocity is 2 m/s, the promotion of increasing of the height of the bottom hole flow bean to the increasing of flow velocity mainly lie in the period when the gap width is not that large. It means The promotion of the bottom hole flow bean height to pipeline self-buried mainly lie in the stage of beginning of erosion as a consequence we must chose suitable height of the bottom hole flow bean to speed up the process of pipeline self-buried.

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