PAPER • OPEN ACCESS

Design of a drilling unit for deep-sea stratum drilling robot

To cite this article: Z Tian *et al* 2021 *IOP Conf. Ser.: Earth Environ. Sci.* **861** 072031

View the article online for updates and enhancements.

Design of a drilling unit for deep-sea stratum drilling robot

Z Tian [1], J Chen[1,2,] P Zhang[1], H Zhu[1], D Ruan[1], and Y Ge[1]

[1]Ocean college, Zhejiang University, Zhoushan, 316021, China
[2] corresponding author's e-mail address: arwang@zju.edu.cn

Abstract. Marine natural gas hydrate has attracted much attention due to its broad energy prospects. With the deepening of research on natural gas hydrate, researchers have found that the decomposition of natural gas hydrate is an important inducer for many natural disasters. This paper proposes a design idea of a deep-sea stratum drilling robot used in gas hydrate test mining area. It can carry out long-term and effective real-time monitoring of the surrounding terrain and environmental changes. The specific structure and function of each component of the robot are introduced, and the locomotion principle of the drilling robot is elaborated. This paper focuses on a drilling unit as one of the key technologies for developing the robot, and the design of drilling unit of robot will be presented in detail. Then, the feasibility of the robot movement and the effect of the drill bit rotation on the soil are obtained through mechanical analysis and simulation. The work of this paper provides guidelines for the development of deep-sea stratum drilling robot in the future.

1. Introduction

In recent years, with the gradual exhaustion of non-renewable resources such as fossil fuels on the earth, the exploration and development of marine gas hydrates with abundant seabed reserves has become the focus of attention of all countries in the world [1-2]. Marine gas hydrate is characterized by high energy density, wide distribution, large scale and shallow burial. Its huge resources and attractive prospects for development and utilization make it considered as a potential important strategic alternative energy source for fossil fuels in the 21st century.

With the deepening of research on natural gas hydrate, researchers have found that the decomposition of natural gas hydrate in the seabed will damage the engineering mechanical structure of seabed sediments, leading to marine geological disasters such as submarine landslides, seriously threatening drilling safety and causing engineering disasters, and the exploitation of natural gas hydrate may also exacerbate the global greenhouse effect and damage the ocean ecological environment [3-5]. However, in the process of further development of natural gas hydrates, it is necessary to overcome the seabed collapse caused by excavation and the possible seabed geological disasters caused by the spontaneous decomposition of natural gas hydrate. Therefore, it is urgently necessary to strengthen monitoring of variation of various characteristics parameters of strata in the trial production area during the exploitation of natural gas hydrate in the seabed, so as to guarantee the smooth progress of the exploitation project. The occurrence environment of marine gas hydrates is located in the deep-sea stratum, as there is no mature on-site monitoring equipment which can work directly in the formation of the trial production area, so it is imperative to develop deep-sea stratum drilling robot. The robot can realize the drilling and steering movement inside the deep-sea stratum, at the same time, the multi-parameter sensors carried by the tail cable can realize in-situ monitoring of the seabed terrain. Figure 1 shows the design concept and application scenario of the drilling robot.
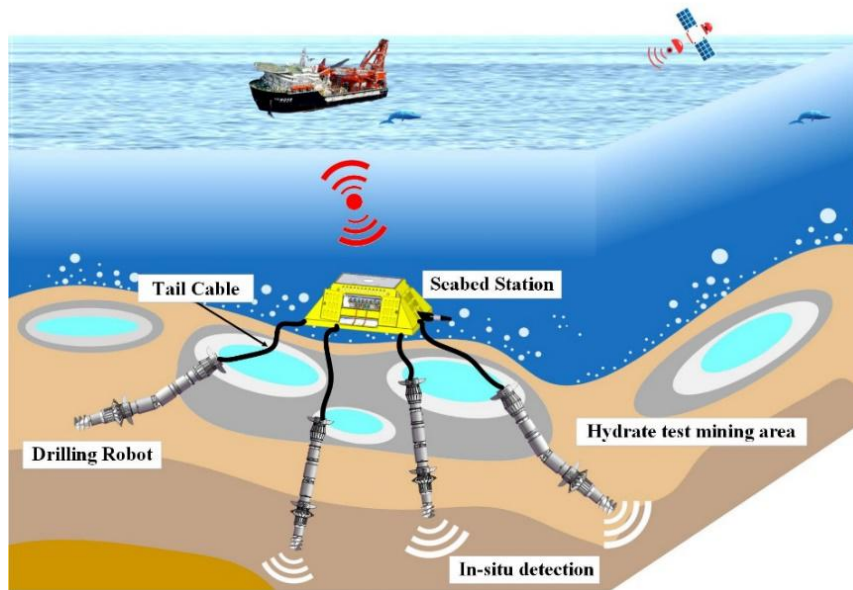
Figure 1. The application scenario of deep-sea stratum drilling robot

At present, a buried-type drilling robot which can be used for autonomous drilling in deep-sea stratum has not been developed. However, a variety of autonomous drilling robots have been proposed for planetary exploration. For instance, the Mobile and Modular Drilling Robot [6], Screw Subsurface Explorer [7] and Digbot [8], low-torque drilling is carried out by rotating screws through its screw-type mechanical structure. Additionally, the bioinspired robots such as the Mole-type Drilling Robot [9] and IDDS [10], the bionic excavation is carried out through the cooperation of the drill and propulsion mechanism. During penetration, the downforce of these drilling robots usually depends only on their own gravity, and they are susceptible to soil pressure. At the same time, the drilled soil cannot be discharged out of the hole by the drilling unit of these robots. As a consequence, these robots cannot drill deep underground.

In this paper, a design idea of a deep-sea stratum drilling robot was proposed to make efforts to solve above mentioned difficulties. And the specific structure and locomotion principle of drilling robot will be elaborated. As one of the key technologies in robot development, we design a new type of drilling unit with expandable drill bit and the effect of the drill bit rotation on the soil are obtained through mechanical analysis and simulation.

2. Concept and movement mechanism of the deep-sea stratum drilling robot

The robot is a multi-unit combined design with a hollow symmetrical structure, which can reduce the volume of the robot while improving the utilization rate of the mechanism space. Figure 2 shows the conceptual model of the deep-sea stratum drilling robot. It comprises of five units: drill bit, anterior support unit, steering unit, propulsion unit and posterior support unit. In addition, an anti-rotation wing plate is installed on the support unit of the robot to prevent the robot from rotating during drilling. The modular structure of the robot has high compatibility and interchangeability. In order to adapt to different working stratum environments, support and propulsion units can be added. The working environment of the robot is a natural gas hydrate trial mining area with a sea depth of 1500-3000 meters. The robot is hydraulically driven, so the power mechanism does not need an additional underwater pressure-resistant sealing structure. The hollow structure enables the power supply oil circuit and control cable to pass through the inside of the robot.
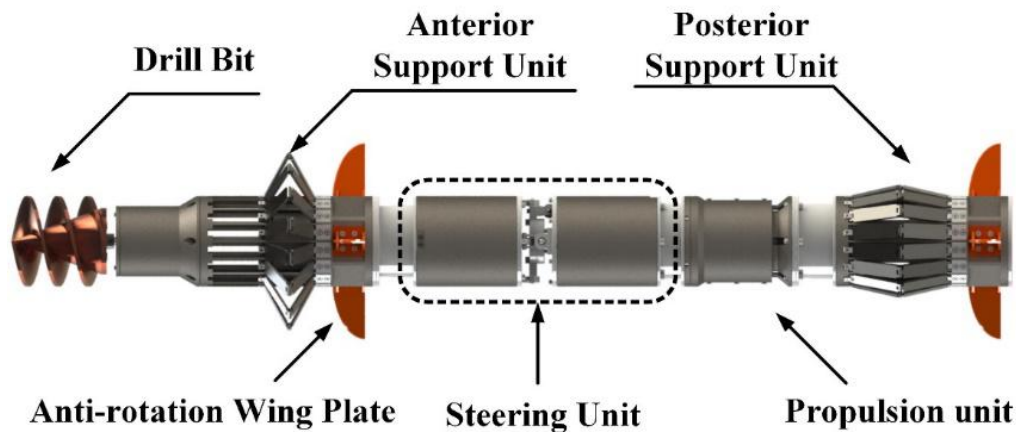
Figure 2. Concept model of the deep-sea stratum drilling robot

During the drilling process, the drill bit excavates a ground and generates a space for locomotion. Through the periodic cooperation of the anterior and posterior support units and the propulsion unit, the robot can achieve peristaltic motion in the seabed, and the realization of the steering function depends on the steering unit. Among them, the support unit is inserted into the soil through expansion to provide support for the downward movement of the robot. Therefore, the robot advances by a propulsive force and does not depend on its own gravity. The movement of the propulsion unit when the support unit is contracted can effectively avoid the influence of soil pressure. Figure 3 shows the locomotion principle of the robot.

The cyclical motion processes of the robot inside the seabed stratum are as follows:

1) The posterior support unit extends, and the posterior support plates expand and insert into the soil.
2) The propulsion unit extends to a certain length according to the drilling speed of the drill bit.
3) The posterior support unit contracts, and the posterior support plates withdraw.
4) The anterior support unit extends, and the anterior support plates expand and insert into the soil.
5) The propulsion unit quickly contracts to the initial state.
6) The anterior support unit contracts, and the anterior support plates withdraw. The robot returns to its original state and completes a cycle of motion.
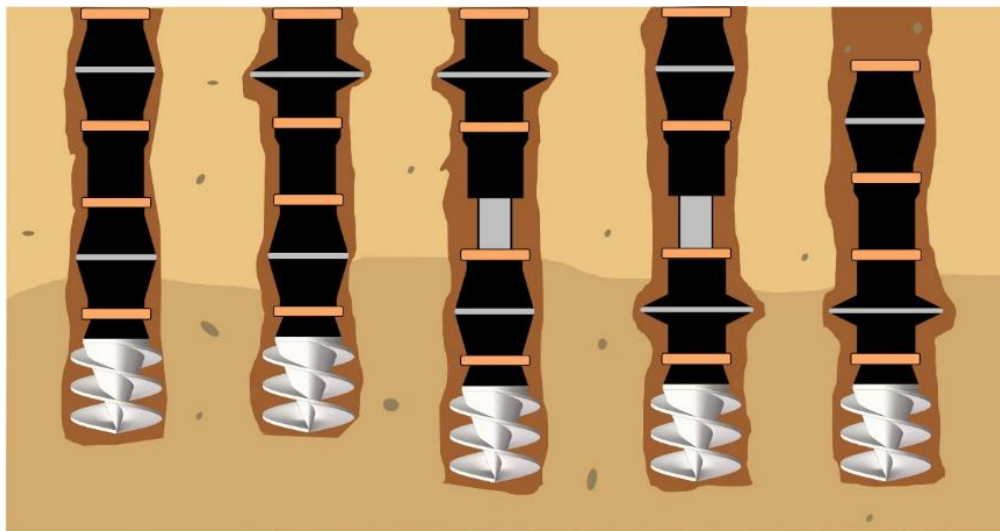

Figure 3. Locomotion principle of the deep-sea stratum drilling robot

In the process of locomotion, the action time of each driving unit of the robot is allocated according to each stage of the motion cycle. A movement cycle of the robot can be divided into six beats, and the actions of each unit of the robot in these beats are shown in Table 1.

Table 1. The movement times table of deep-sea stratum drilling robot

	1	2	3	4	5	6
Drill bit		Rotate				
Anterior support unit				Extend		Contract
Steering unit						
Propulsion unit		Extend			Contract	
Posterior support unit	Extend		Contract			

3. Design and modelling of drilling unit

3.1. Expandable-type drill bit

Figure 4 shows the overall structure of the robot drilling unit. The drill bit is driven by hydraulic motor and located at the front end of the robot, which provides the cutting force and torque required by the robot. During the drilling process, the drill bit excavates a ground and generates a space for locomotion. This requires the design of the bit to meet two functions: longitudinal excavation of soil, lateral compaction of drilling cuttings to both sides.
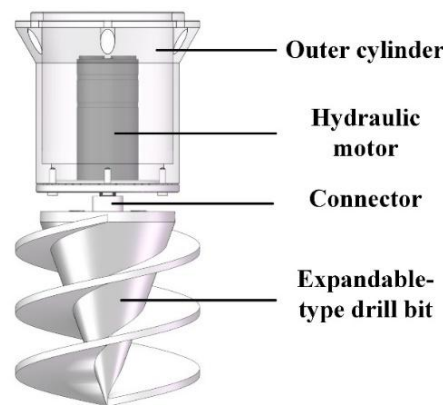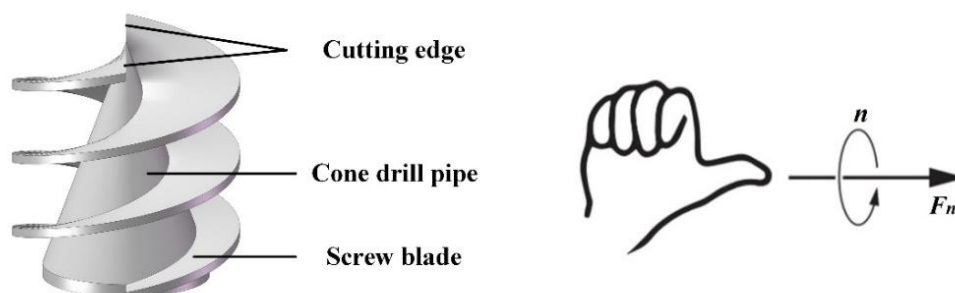

Figure 4. Structure of drilling unit

Figure 5 shows the detailed structure of expandable-type drill bit. Different from the traditional twist bit, the main body of the expandable-type drill bit is conical drill pipe with equal pitch screw blades, and the front end of the bit is a cutting edge with a certain angle. During the drilling process, the drill cuttings can be transported backwards through the screw blades while the drill bit cuts the soil. The function of the conical drill pipe is to compress and expand into the surrounding soil, forming a circular hole that matches its appearance. This will effectively reduce the drilling resistance and greatly improve the drilling efficiency of the robot in the seabed.

Figure 5. Detailed structure of expandable-type drill bit

3.2. Analysis of drilling process

3.2.1. Analysis of Cone Drill Pipe Expansion

During the downward drilling process of the drill bit, the cone drill pipe will exert its own expansion effect, and finally a hole with the same diameter as the drill bit will be formed. Given an observation point, from the horizontal view of the observation point, the diameter of the hole at the observation point increases gradually with the advance of the drill bit. The enlargement of the hole diameter in the observation plane is a typical problem of cylindrical hole expansion. Figure 6 shows the change of the hole diameter when the bit is drilling one pitch from t_1 to t_2.
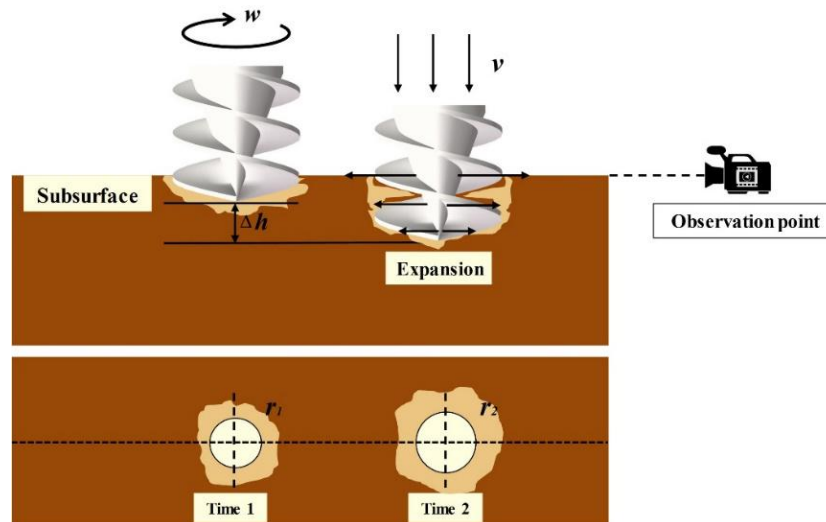

Figure 6. Aperture expansion

During the drilling process, the cone drill pipe always keeps close contact with the soil, and the contact surface produces a fixed pressure on the soil. The diameter of the soil hole is continuously enlarged to the maximum diameter of the cone. The conical drill pipe is subjected to the drilling pressure F_R and the direction is downward along the axial direction; the direction of soil pressure N_1 and N_2 on the cone is perpendicular to the cone upward. The frictional forces f_1 and f_2 between the soil and the cone surface, the direction is upwards along the cone surface. Figure 3 shows the force analysis of conical drill pipe.
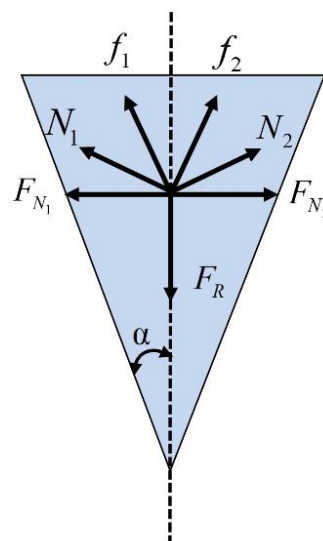

Figure 7. The diagram of forces on conical drill pipe

In the state of force balance:

$$\begin{cases} N_1 \cos\alpha + f_2 \sin\alpha = N_2 \cos\alpha + f_1 \sin\alpha \\ 2\left(N_1 \sin\alpha + f_2 \cos\alpha\right) = F_R \\ f_1 = \mu N_1 \\ N_1 = N_2 \end{cases} \tag{1}$$

where α is the drill pipe cone angle, μ is the friction coefficient between drill pipe surface and soil.

The horizontal expansion force at any point on the drill pipe can be obtained by sorting out and solving the above formula.

$$F_{N_1} = \frac{F_R(\cos\alpha + \mu\sin\alpha)}{2(\sin\alpha + \mu\cos\alpha)} \tag{2}$$

3.2.2. Analysis of drilling cutting load

The cutting edge is a three-dimensional rotary cutting state during the drilling process. The cutting edge of the front end of the drill bit belongs to the category of wide cutting tools [11]. The failure mode of soil during cutting is crescent failure [12-14]. The soil unit where the crescent failure occurs flows forward, to both sides and upwards, and the boundary of the soil surface failure is like a crescent. As shown in Figure 8 (a), the crescent failure consists of three failure areas: a central failure area directly ahead of the cutting edge and a lateral failure area symmetrically arranged on both sides of the central failure area. During the cutting process of the drill bit, the cutting edges at both ends of the cutting tool have no lateral damage to the soil, so the cutting tool only causes central failure of the soil. The influence of gravity of failed soil unit on cutting resistance can be neglected. Based on the central failure form of soil, a micro-element cutting load model of cutting edge is established as shown in Figure 8 (b).
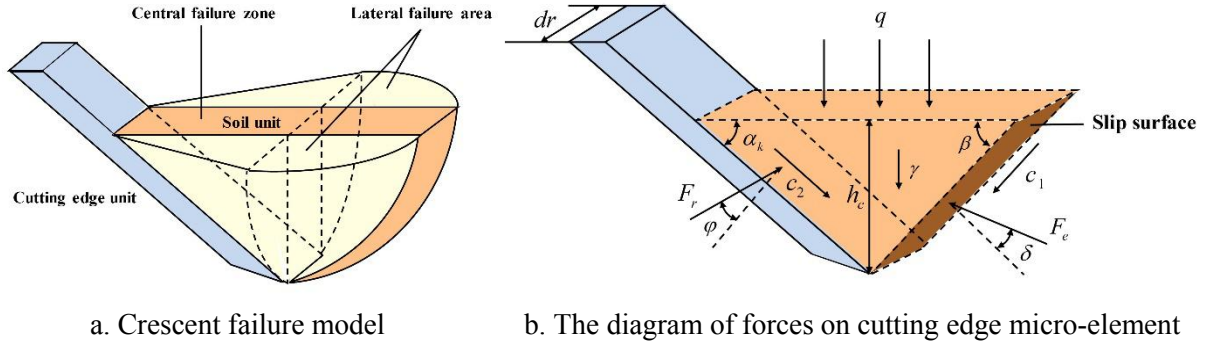

a. Crescent failure model   b. The diagram of forces on cutting edge micro-element

Figure 8. Cutting edge cutting load model

The spiral cutting of cutting edge is simplified to the inclined plane cutting with the same inclination angle as the spiral. The central failure area is simplified as a wedge block with the width of the micro-element of cutting edge. The limit mechanical equilibrium equation of the central failure region of soil micro element is as follows.

$$\begin{cases} F_r \sin(\alpha_k + \varphi) = F_e \sin(\delta + \beta) + ch_c \cot\beta\,\mathrm{d}r \\ F_r \cos(\alpha_k + \varphi) + F_e \cos(\delta + \beta) = q\rho\,\mathrm{d}r + \dfrac{h_c \rho\gamma g\,\mathrm{d}r}{2} + ch_c\,\mathrm{d}r \end{cases} \tag{3}$$

where, F_r is the resultant force of cutting edge micro-elements on soil micro-elements; F_e is the resultant force of the surrounding soil on the soil unit; β is the soil failure angle, characterize the angle between the soil slip surface and the cutting speed direction; α_k is the cutting angle; h_c is the

depth of cutting; $\mathrm{d}r$ is the length of cutting edge unit; c is the soil cohesion; γ is the soil bulk density. According to the geometric relationship: $\rho = h_c(\cot\alpha + \cot\beta)$.

The force F_r is derived as:

$$F_r = \frac{\left[ch_c \cot\beta + \tan(\delta+\beta)(q\rho + \dfrac{h_c\rho\gamma g}{2} + ch_c) \right]\mathrm{d}r}{\sin(\alpha+\varphi) + \cos(\alpha+\varphi)\tan(\delta+\beta)} \tag{4}$$

According to the Terzaghi K's soil failure theory [15], the soil failure surface is the shear surface corresponding to the minimum cutting resistance. According to this principle, β can be solved by the following partial differential equation:

$$\partial F_r / \partial\beta = 0 \tag{5}$$

The expression for β is

$$\beta = \frac{\pi}{2} - \frac{\alpha_k + \delta + \varphi}{2} \tag{6}$$

The cutting resistance moment in the horizontal direction of the cutting edge is as follows:

$$M_H = \sum_{i=1}^{n_i} \int_0^w F_r \sin(\alpha_k + \varphi)(r_s + \frac{dr}{2})dl \tag{7}$$

Where, n_i is the number of cutting edges; r_s is the distance to the center of rotation; w is the width of the cutting edge.

3.3. Simulation of the drilling process about the robot's drill bit

During the drilling process, the drill bit will excavate a ground and generate a space for locomotion. In order to verify the rationality of expandable-type drill bit design. The explicit dynamics module of ABAQUS software is used to simulate the drilling process of the bit. When setting parameters, the soil type was set to saturated clay, the drill bit was made of steel, and the rotate speed of the drill was set to 5 r/s. The physical properties of the steel and soil used in the simulation are shown in table 2 below.

Table 2. Material properties for analysis

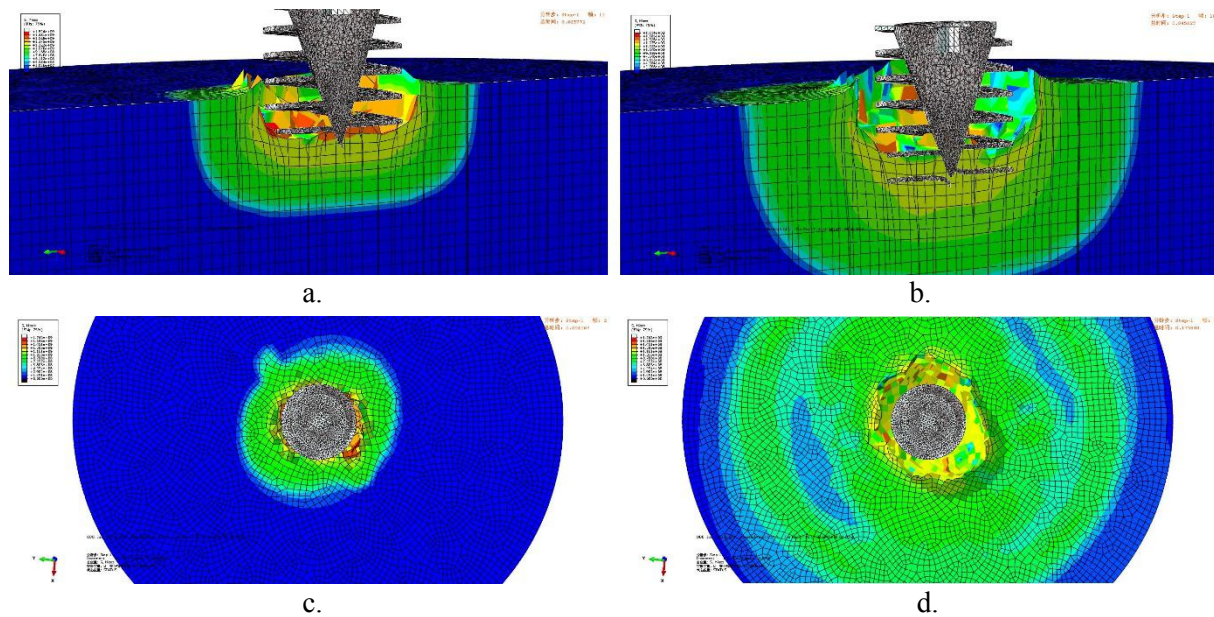| Material	Property	Unit	Value
Steel	Young's modulus	MPa	2×10^5
	Tangent modulus	MPa	21
	Density	kg/m³	7,800
Soil	Density	kg/m³	2×10^3
	Poisson's ratio	-	0.5
	Internal friction angle	-	20°
	Cohesion	kPa	15
Steel-Soil	Coefficient of static friction	-	0.35
	Coefficient of dynamic friction	-	0.3

a.

b.

c.

d.

Figure 9. The deformation trend of soil during drilling. a.- b. The cross-sectional views of the simulation model at different times during the drilling process. c.- d. The top views of the simulation model at different times.

Figure 9 shows the simulation results. It can be seen the flow trend of the surrounding soil during the drilling process of the drill bit. It is obvious that as the drill bit is drilled, the hole diameter in the soil continues to expand until it is the same size as the drill bit. This is in line with the expected results. The range of the drill bit disturbing the soil is about twice its own diameter, and the diameter of the severely deformed soil area is 1.2-1.5 times the diameter of the drill bit. At the same time, we can see that the tip of the drill bit has been embedded in the soil, and the soil on the spiral blade has not been cut. The reason is that the rotation speed of the drill bit is too high, and the various mechanical parameters of the simulated submarine soil used in the simulation model are not actual conditions. The physical parameters of the soil in the submarine gas hydrate trial mining area are currently difficult to obtain, so it is necessary to improve the simulation model under more realistic conditions to obtain better simulation results.

4. Conclusion

In this paper, a deep-sea stratum drilling robot is designed, which can be applied to gas hydrate test mining area. The specific structure and function of each component of the robot are introduced, and the locomotion principle of the drilling robot from the seabed into the stratum of the mining area is elaborated. Furthermore, a drilling unit based on expandable bit is designed for the robot to reduce drilling resistance. The drilling process of expandable bit is analysed theoretically. Then through simulation analysis, it was verified that the deformation trend of the soil during the drilling process of the drill bit was consistent with the expectation. This work provides significant theoretical basis for future optimization and experiment.

In the future work, we will design a robot prototype. The complex motion of the whole robot in the stratum is modeled and analysed, then we can complete the movement control of the robot.

References

[1]   Dai J, Niranjan B, Diana G and Nader D 2008 Exploration for gas hydrates in the deepwater, northern Gulf of Mexico: Part II. Model validation by drilling *Marine and Petroleum Geology* 25(9)

[2]   C Zhu, M Zhang, X Liu 2017 Gas hydrates: Production, Geohazards and Monitoring *Journal of Catastrophology* 32(3)

[3]   León R, Llorente M, Giménez M, Carmen J 2021 Marine Gas Hydrate Geohazard Assessment on the European Continental Margins *Applied Sciences* 11(6)

[4]   Daniel R. Mc Connell, Z Zhang, Ray B 2012 Review of progress in evaluating gas hydrate drilling hazards *Marine and Petroleum Geology* 34(1).

[5]   Carolyn D. Ruppel, John D 2017 The interaction of climate change and methane hydrates *Reviews of Geophysics* 55(1)

[6]   Becker F, Boerner S, Lichtenheldt R 2016 Enabling Autonomous Locomotion into Sand-A Mobile and Modular Drilling Robot *Proceedings of ISR 2016: 47st International Symposium on Robotics* VDE 1-6.

[7]   Nagaoka K, Kubota T, Otsuki M 2009 Robotic screw explorer for lunar subsurface investigation: Dynamics modelling and experimental validation *International Conference on Advanced Robotics IEEE* 1-6.

[8]   Abe R, Kawamura Y, Kamijima K 2010 Performance evaluation of Contra-Rotating drill for DIGBOT *IEEE*

[9]   Kubota T, Nakatani I, Watanabe K 2005 Study on Mole-Typed Deep Driller Robot for Subsurface Exploration *IEEE International Conference on Robotics & Automation*

[10]   Rafeek S, Gorevan S P, Bartlett P W 2001 The Inchworm Deep Drilling System for Kilometer Scale Subsurface Exploration of Europa (IDDS) *Forum on Innovative Approaches to Outer Planetary Exploration* 2001-2020

[11]   Godwin R, Dogheny M J 2007 Integrated soil tillage force prediction models *Journal of Terramechanics* 44 (1): 3—14

[12]   Mckyes E 1989 Agricultural Engineering Soil Mechanics *Amsterdam: Elsevier*

[13]   Mckyes E, Ali O S 1977 The cutting of soil by a narrow blade *Journal of Terramechanics* 14(2) : 43-58

[14]   Mckyes E, Desir F L 1984 Prediction and field measurements oftillage tool draft forces and efficiency in cohesive soil *Soil Tillage Research* 4(5): 459-490

[15]   Terzaghi K. 1965 Theoretical soil mechanics *Hoboken, New Jersey John Wiley& Sons*