

INNOVATIVE TECHNOLOGIES OF OIL AND GAS

RESEARCH ON THE PHYSICAL STRENGTH OF SURFACE CONDUCTOR SOIL UNDER DEEP JET DRILLING

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The installation of a surface conductor in deepwater jet drilling is crucial for offshore oil and gas development. This study investigates the interaction between the surface conductor and subsea soil during injection drilling. A simplified model using ABAQUS finite element software analyzes the damage effect of the water jet on the soil and simulates the mechanism of soil body damage under different parameters. The mechanical behavior of the soil and conductor during installation is examined, and the load-bearing characteristics of the soil are analyzed. Sensitivity analysis of factors such as injection displacement and bit extension reveals their significant influence on conductor installation. The findings provide insights into the drilling process and contribute to ensuring the stability of the wellhead in deepwater drilling operations.

Keywords: jet drilling, surface catheter, stability mechanism, finite element analysis.

1. Introduction

The surface layer of soil in shallow water is relatively hard, similar to the way of drilling on land, and the surface conductor operation method is generally used to drill down the casing and then cement the well [1-5]. The surface soil under water in deep water is looser and softer, and the conventional drilling operation method is more difficult than and requires longer operation time, which is time costly and not suitable for the high efficiency of deepwater drilling [6-10]. At present, deepwater drilling at home and abroad adopts the jetting in method, which uses the weight of the downhole drilling tool plus the high-pressure water jet pumped by the jet pump to realize the drilling and lowering of the conductor at the same time [11-16]. Deepwater drilling has been researched overseas since the early 1960s, when it was first used in the Gulf of Mexico to develop offshore oil and gas fields with high operational efficiency [17].

Minton [18] proposed the catheter injection method before the 1970s, which was applied to the drilling construction of drill ships in the Gulf of Mexico waters. At that time, jet drilling used a combination of powered drilling tools, and during the jet drilling process, drilling fluid was pumped in using a mud pump to form a high-pressure water jet at the nozzle, and after the high-pressure water jet was ejected from the broken soil layer, the drilling fluid carrying rock chips was returned to the bottom

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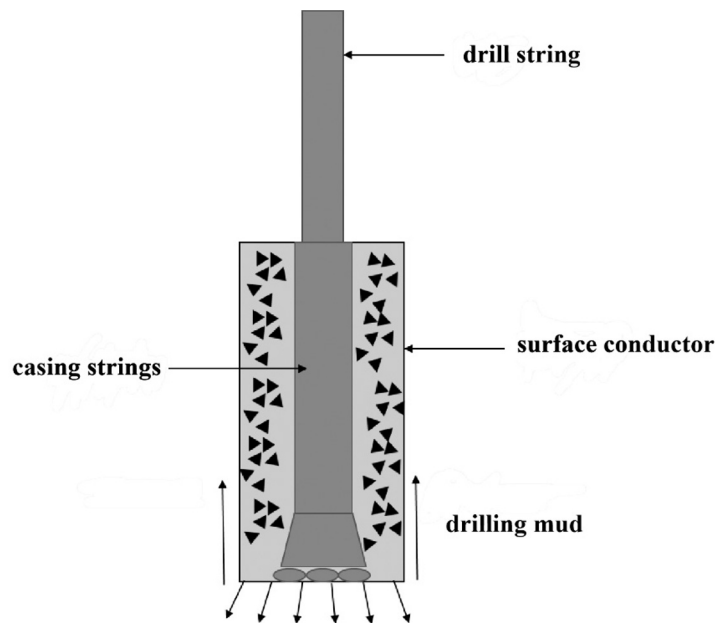


Fig. 1. Outer circulation injection diagram

of the well by the annulus between the pipe and soil, and the method shown in **Figure 1** was called the external circulation method [19].

King et al. [20] showed that the design and installation of deepwater surface conductor is not independent in 1995, but also needs to consider the related factors such as water trap, pile foundation, installation condition, and stress load, etc. Because the model is built under a large number of assumptions, the model results are not guaranteed to fully reflect the real situation.

In 2002, Philippe [21] gave a calculation method of conductor bearing capacity, which can calculate the instantaneous bearing capacity of surface conductor installation and the bearing law of soil strength change with time, and derive the formula for calculating the strength of conductor under certain load conditions, and proved to be effective when applied in oil fields in the Gulf of Mexico waters.

In 2005, domestic started to cooperate with foreign oil companies to explore offshore oil and gas projects. In 2007, Husky[22] Oil Company completed the first Li-wan 3-1-1 well in the South China Sea in China with a water depth of over 1,000 m, and successfully applied the injection technology to install surface conductors to the domestic South China Sea site.

Based on literature research [23-31], the following issues are identified.

1. The interaction between the casing and the formation during the process of deepwater jet drilling is highly complex. The dynamic drilling process lacks a precise mathematical description, making it challenging to model the interaction between the formation and the surface conductor accurately.

2. The bearing capacity of the surface conductor during the jetting installation process undergoes changes at different stages of the drilling process. There is insufficient understanding of the real-time variations in the bearing capacity. Jetting parameters are crucial for successful jet drilling, but there is currently no quantitative model to describe the impact of these parameters on the stability of the drilling process and the mechanisms by which the soil is disturbed. As a result, a unified calculation model is lacking.

3. Some jet drilling procedures lack scientific design methods and quantitative analysis of drilling parameters, relying heavily on empirical knowledge. For instance, there is a lack of scientific design regarding parameters such as jetting volume, drill string configuration, installation depth of surface conductor, and idle time during drilling. The design of these parameters is predominantly based on experience, resulting in a relatively conservative approach.

The currently more mature method for jetting installation of casings is the “internal circulation” method, as illustrated in **Figure 2**. In this method, high-pressure water jets act on the formation, and the water jet’s mud carries debris from the annular

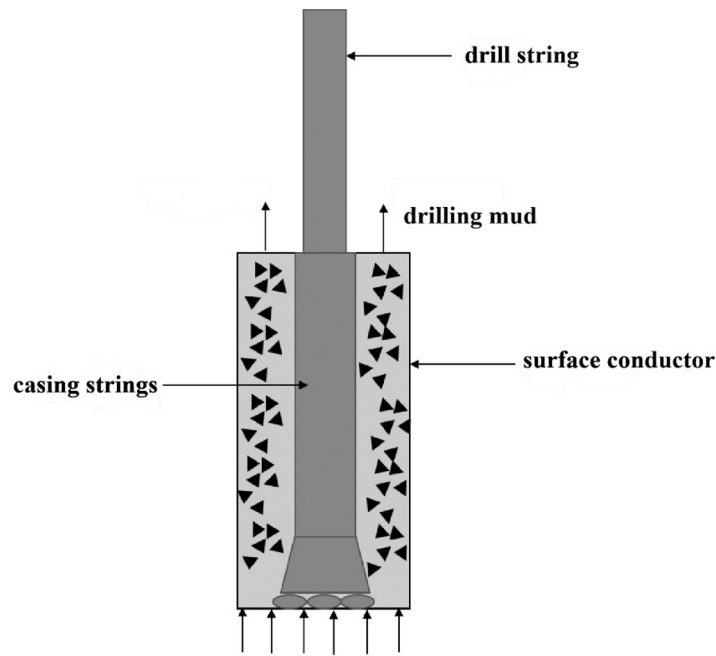


Fig. 2. Internal circulation injection diagram

space between the casing and the drill bit, returning it to the surface at the underwater wellhead. After jetting forms the borehole, the casing is pushed into the formation by its own weight and the downhole power drilling tools, creating a stable drilling channel. The process of internal mud debris return ensures the stability of the external formation around the casing, thereby enhancing the casing's bearing capacity and stability [32-36].

2. Research approach

This paper aims to investigate the impact of seabed soil properties and drilling parameters on the bearing capacity of surface conductor, as well as the effects of different drilling parameters on the stability of surface conductor and soil disturbance during deepwater jetting installation. The research methodology includes a comprehensive literature review, theoretical analysis, and numerical simulations.

To establish a computational model for analyzing the interaction between the surface conductor and the soil, the study will employ the principles of effective stress and the theory of submerged water jet. The simplified model of soil-casing interaction during the jetting process will be developed using the ABAQUS finite element software. This model will enable the simulation and analysis of soil disturbance mechanisms under various drilling parameters.

To assess the sensitivity of stability parameters, the research will focus on conducting a systematic investigation of the impact of different parameters on the deepwater jetting installation of surface conductor. Through the integration of literature review, theoretical analysis, and numerical simulations, this study will contribute to a better understanding of the factors influencing the stability and performance of surface conductor in deepwater jetting installations.

3. Model building theory

3.1. The theory of water jet breaking soil

When a water jet impinges on soil, the soil undergoes jet reflection, resulting in a change in the jet direction. A fraction of the jet's energy is dissipated, exerting a continuous impact on the soil in the form of a reactive force. Let ρQu and $\rho Qu \cos\phi$ denote the momentum of the water jet before and after soil impingement, respectively. According to the principle of momentum conservation:

$$F = \rho Qu(1 - \cos\phi), \tag{1}$$

where ρ represents the jet density (kg/m^3); Q denotes the jet flow rate (m^3/s); u denotes the jet flow velocity (m/s); φ is the jet reflection angle.

3.2. Effective stress principle

The forces transmitted by the soil skeleton in deepwater surface soils are called effective stresses, and the variation of effective stresses has a direct effect on the compressive deformation and shear strength of the soil [37]. Deep-water surface clay is a saturated soil, consisting of water between the soil skeleton and the skeletal gap, which is shared by both after being subjected to external loads, but only the effective stress transmitted through the skeleton can deform the soil.

The effective stress is the total stress minus the pore water pressure:

$$\sigma = \sigma - u, \quad (2)$$

where σ is the effective stress; σ is the total stress; u is the pore water pressure.

Eq. 2 is expanded by matrix as:

$$\begin{bmatrix} \sigma'_x & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma'_y & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma'_z \end{bmatrix} = \begin{bmatrix} \sigma_x & \tau_{xy} & \tau_{xz} \\ \tau_{yx} & \sigma_y & \tau_{yz} \\ \tau_{zx} & \tau_{zy} & \sigma_z \end{bmatrix} - \begin{bmatrix} u & 0 & 0 \\ 0 & u & 0 \\ 0 & 0 & u \end{bmatrix}. \quad (3)$$

For the deep water submarine soil, the stress analysis of the deep water surface soil without wave and other force disturbance is shown in **Figure 3**.

The total stress magnitude is given by

$$\sigma = \gamma_1 H_1 + \gamma_2 H_2. \quad (4)$$

The pore water pressure is

$$u = \gamma_1(H_1 + H_2). \quad (5)$$

The above equation can be combined to obtain the effective stress in the soil:

$$\sigma' = \sigma - u = \gamma_2 H_2 - \gamma_1 H_2. \quad (6)$$

It can be seen that: the effective stress of the soil is only related to the difference between the capacitance of the soil and the seawater (the effective capacitance of the soil) and the thickness of the surface soil, and is not related to the depth of the seawater. Therefore, the seawater pressure has no effect on the deformation, stress and strain of the surface soil body. Therefore, in the

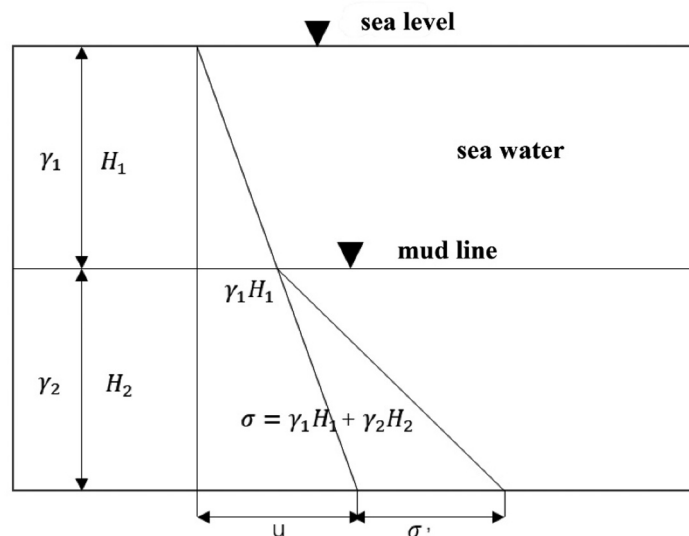


Fig. 3. Stress analysis diagram of submarine soil

process of establishing the surface conductor model for jet installation, it is not necessary to consider the depth of seawater, but only the impact of jet impact and drilling pressure on the surface soil body.

When the average force on the soil acting on the jet water jets is greater than the critical damage pressure of the soil, the soil is damaged. In the process of jet drilling, the subsea shallow clay is mainly damaged by the shear of the water jet, so the value of the undrained shear strength of the soil can be approximated as approximately equal to the value of the critical damage pressure of the soil, which can be obtained as:

$$P_{cr} = c_u \tag{7}$$

Then the soil is destroyed under the condition that

$$P_b \geq c_u \tag{8}$$

where P_{cr} is the critical breaking pressure of the soil (Pa); P_b is the force per unit area of the jet acting on the soil body (Pa).

3.3. Calculation of conductor bearing capacity

The force state of surface conductor in deepwater jet drilling is extremely complicated, in order to determine the installation depth of surface conductor, it is firstly necessary to establish the bearing model of conductor lowering into place, and analyze the force situation in different stages of jet drilling. Many researchers and scholars at home and abroad, in the research process of determining the depth of surface conductor installation in deepwater jet drilling, mainly divide the surface conductor force into four stages: the stage of conductor jetting into the stage, the stage of conductor lowering into place, the stage of hanging the surface conductor and the stage of cementing mud to reach the bottom of the borehole [38].

The objective of this study is to investigate the mechanical analysis of the surface conductor during the jetting advancement process. The axial load is the primary influencing factor for casing advancement, while there is also lateral frictional resistance between the surface conductor wall and the soil. However, due to the low cohesive strength and high pore water pressure of deepwater surface soil, the impact of lateral frictional resistance is minimal, resulting in a minor effect on casing advancement. Therefore, the focus of this study is primarily on analyzing the axial load, which includes the weight of the casing string, the weight of the drill string, the bottom drilling pressure, the lateral frictional resistance, and the upward force on the casing.

Based on **Figure 4**, the axial equilibrium equation during the casing jetting advancement process can be expressed as follows:

$$N_1 + N_2 + N_3 + W_3 = W_1 + W_2 \tag{9}$$

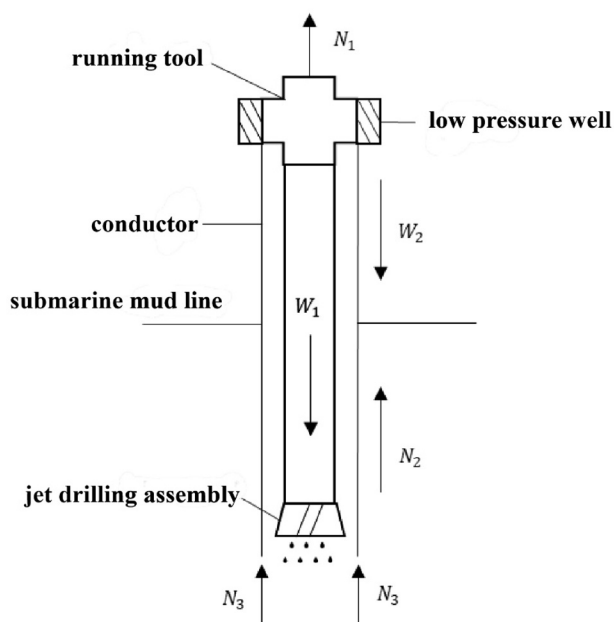


Fig. 4. Analysis diagram of the force on the catheter during injection

where N_1 is the axial load of the upward pipe string (kN); N_2 is the lateral frictional resistance of the casing (kN); N_3 is the reaction force of jetting (kN); W_1 is the weight of the drill string in seawater (kN); W_2 is the weight of the casing in seawater (kN); W_3 is the pressure exerted on the seabed soil by jetting (kN).

4. Model establishment

The model is mainly intended to study the damage to the surface soil during jet drilling, the trend of stress and displacement changes in the surface soil under different parameters, so the upward return debris carried by the jet water jet breaking the soil and the downhole power drilling tools are discarded. Now the model only has the drill bit, the conductor and the surrounding soil, and the conductor size of 36in is assumed in advance to build the model, and the conductor size in the model will be modified later when the effect of different conductor sizes on jet drilling is studied.

In domestic deepwater drilling sites, a combination of matching drilling tools with conductor sizes of 36 in (914.4 mm), 30 in (762 mm), and 26 in (660.4 mm) is generally used, and the effect of the injection drilling operation process on the surrounding soil can be neglected when the soil is modeled to be 10-20 times the size of the soil [39].

Simplifying the jet drilling process and using the jet impact force to simulate the damaging effect of the jet in the water during drilling, according to the effective stress principle, so it is not necessary to consider the pressure effect of the deep water on the soil body, so that the model can be simplified.

The simulation model is built according to the actual construction parameters of the drilling project, and the basic geometric parameters of the modeling are shown below.

Parameters of conductor	Number
Outer diameter (mm).....	914.4
Length (m)	80
Conductor thickness (mm).....	25.4
Diameter of soil body (m).....	20

According to the previous modeling conditions assumptions, a 36 in conductor was selected to create the model, and the outer diameter of the conductor was 914.4 mm. In order to eliminate boundary effects, the soil model size was built to be 20 times the diameter of the conductor, and a two-dimensional axisymmetric finite element model containing three components, including the drill bit, the conductor and the soil, was created. As shown in **Figure 5**.

The deep water surface soil shows both elasticity and plasticity, so the surface soil is analyzed according to the elastic-plastic body, and there are various plasticity intrinsic models in ABAQUS software, and the Mohr-Coulomb model, which is widely used in engineering, is used in this model.

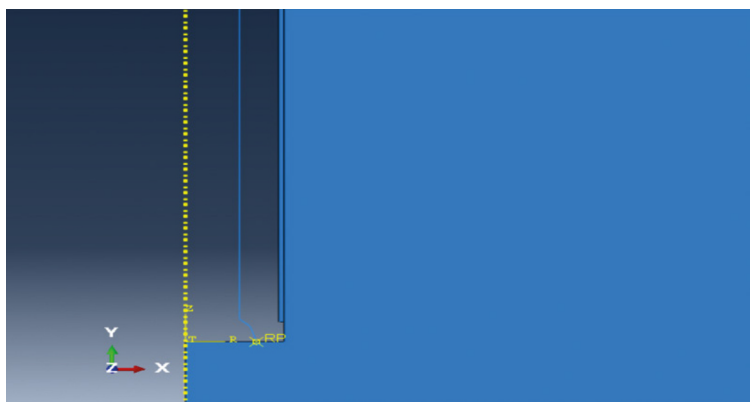


Fig. 5. Geometric modeling

The main parameters are shown below.

Modulus of elasticity (kPa).....	30
Poisson's ratio	0.35
Density (kg/m ³).....	2400
Angle of internal friction (°)	25
Cohesion (kPa).....	18

The material property of the conductor is set to elastic material, according to the engineering example, where the modulus of elasticity is set to 206 GPa, Poisson's ratio is set to 0.3, and the density is 7850 kg/m³. The drill bit is set as a rigid body.

5. Modeling results

When the deep-water jetting method is used to undercut the surface conductor, the drill bit does not directly cut the soil, but the nozzle ejects a high-speed jet impact to destroy the soil, and large deformation and shear breakage occurs to form the borehole [40-43]. In order to study the changes of the displacement and stress fields of the soil by the jet displacement, it was determined that the drill bit extension and the drill bit size were unchanged and the hydraulic jet displacement was changed for qualitative analysis.

The soil displacement stress clouds were determined for a drill bit extension of 100 mm and a drill bit size of 36 in (914.4 mm), and the four values of displacement volumes of 2400 L/min, 3000 L/min, 3600 L/min, and 4200 L/min are discussed.

5.1. Analysis of injection displacement simulation results

From **Figure 6**, it can be seen that the stress value concentrated around the borehole is larger and the range of the stress field is wider when the injection displacement is larger for different injection displacements.

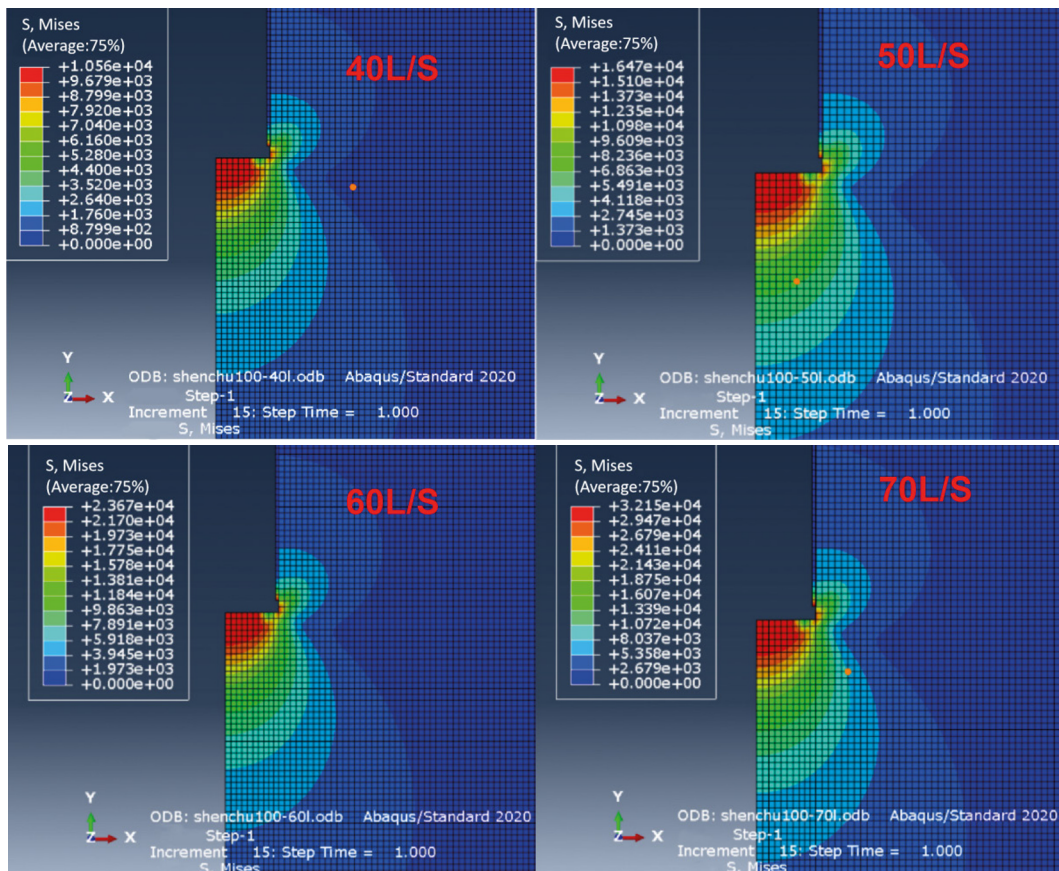


Fig. 6. Stress nephogram of soil and conductor with different injection displacement (a)

5.2. Trends in the impact of injection displacement

The stress cloud diagram can only reflect that the displacement is positively correlated with the stress magnitude, and the larger the injection displacement, the larger the stress value and range, which cannot qualitatively study the trend of the injection displacement on the change of the stress field. Therefore, two paths in the axial and radial directions were created with nodes in the ABAQUS software, and the stress data in the axial and radial directions were extracted and analyzed to quantify the changes of the jet displacement on the stress and displacement values.

The radial and axial directions are shown in **Figure 7**.

Analysis of radial stress displacement results in boreholes with different injection displacements. The radial data is exported by setting the radial path, as shown in **Figure 8**.

From the above stress data and graphs, it is clear that the discharge volume is positively correlated with the axial stress value of the soil, and the larger the discharge volume, the larger the stress value. Along the axial direction of the borehole, the stress value does not vary much within the injection range, 0~0.3m from the center of the borehole, and the stress value decreases gradually from the injection range outward, with a larger decrease. Stress concentration occurs in the soil at 0.55 m axially, which is the location of the lower end of the conductor wall, indicating that the soil in the center of the borehole is extruded to the pipe wall

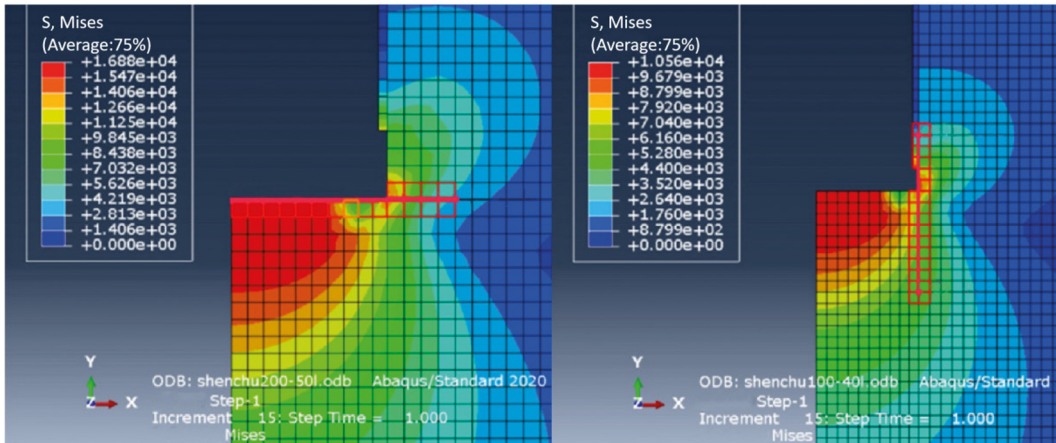


Fig. 7. Radial and axial paths

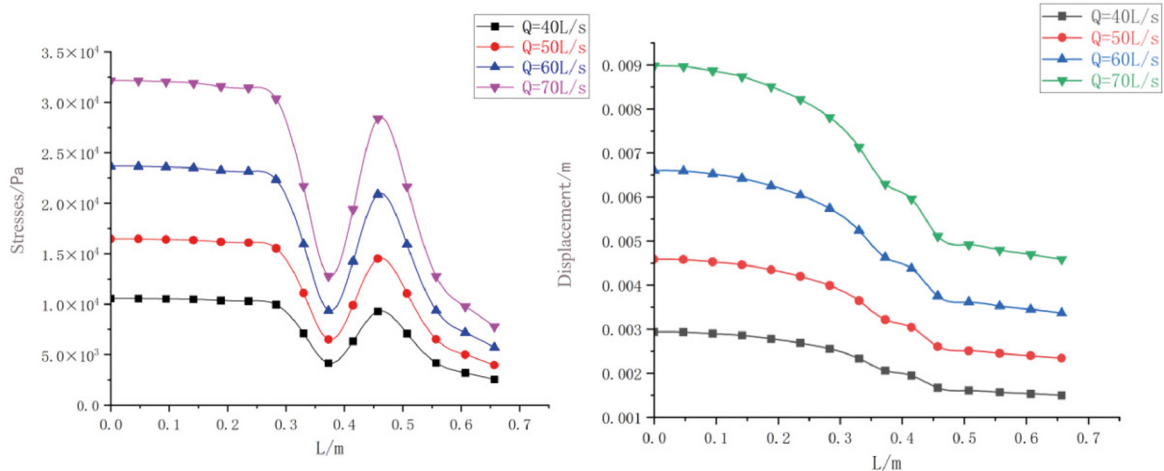


Fig. 8. Effect of displacement on radial stress displacement field

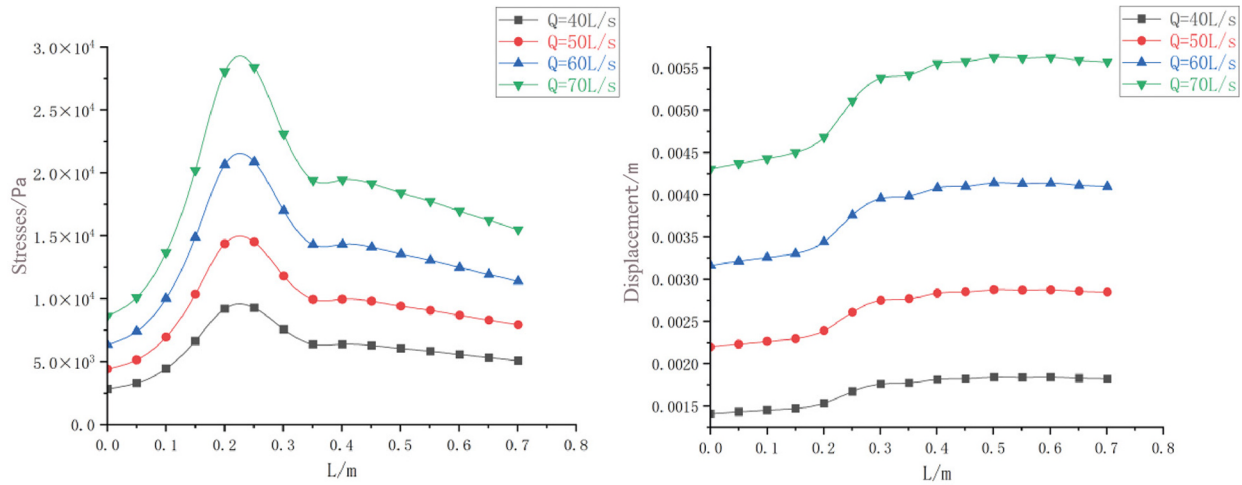


Fig. 9. Effect of displacement on axial stress displacement field

attachment during the injection process, indicating that the soil within the injection range is mainly shear damage and the soil outside the injection range is extrusion damage.

From the displacement data and graphs, it can be seen that the soil displacement is smaller as it gets farther away from the borehole center, and there is no sudden change in displacement with stress concentration, indicating that the damage occurs first in the borehole center under hydraulic injection, and then expands along the distal end of the damage surface toward the borehole center.

Analysis of axial stress displacement results in boreholes with different injection displacements. The axial data is exported by setting the axial path as shown in **Figure 9**.

From the above stress data and graphical trends, it can be seen that the stress is also positively correlated with the injection displacement, and the larger the hydraulic injection displacement, the larger the stress value. However, in the axial path with the same displacement, the highest value of stress is not at the bottom of the well, but at the location of the conductor and the lower end near the soil, where stress concentration occurs; the stress value decreases along the lower end of the conductor to both sides, with the lower end slowing down to a lesser extent and the upper end slowing down to a greater extent, which is related to the distance from the injection, the further away the stress value is, the smaller the stress value is.

As can be seen from the displacement data and displacement curve, in the axial downward direction, the soil displacement gradually increases, the soil displacement outside the surface conductor wall is smaller and less damage, the soil is held against the conductor wall, the lower end is exposed to the soil surface of the water jet, the soil displacement gradually increases, and the effect of hydro-jet breaking is becoming more and more obvious.

6. Conclusions

Based on the theory of the model established in the previous paper, the interaction with the soil when installing the surface conductor at different injection displacements (40 L/s-50 L/s-60 L/s-70 L/s) was simulated. It is concluded that the larger the injection displacement, the greater the hydraulic jet force, the larger the soil stress displacement field, the obvious effect of hole expansion, and the better the lowering of the conductor, but too large an injection displacement will make the soil at the bottom of the borehole over-scouring, and the bearing capacity of the surface conductor decreases.

Two paths of borehole radial and borehole wall axial were set, and the stress and displacement data on the two paths were derived, and the trends of soil stress and displacement in borehole radial and borehole wall axial were obtained. It was found that the stress displacement value in the radial direction decreased outward with the center of the borehole, and the stress concentration phenomenon appeared in the injection action range; in the axial direction, the stress displacement value was the largest at the location of the exposed conductor from the bottom of the borehole.

Acknowledgments

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