Analysis of the through Capacity of Downhole Dynamic Drilling Tools for Short Radius Horizontal Wells in Slim Hole

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Abstract: When sidetracking from a casing window into a slim-hole short-radius horizontal well, operating the screw drilling tool poses significant challenges. The pronounced curvature of the drilled hole, coupled with the considerable structural bending angle, complicates both the triping in and drilling processes. The passing ability of 3°-1.5°double-bend screw drill was modeled and analyzed and it was found that the double-bend screw drill can pass through the casing section. For the open hole section, the allowable weight on bit for the double-bend screw drill to pass through under different borehole curvatures were determined based on the contact force conditions, strength conditions, and friction resistance conditions using finite element simulation. The results are as follows: the double-bend screw drill can be tripped in smoothly and safely with a weight on bit ranging from 1T to 3T and a curvature radius of 30m; it can be tripped in smoothly and safely under the weight on bit ranging from 1T to 2.5T and a curvature radius of 20m; it can be tripped in smoothly and safely under weight on bit ranging from 1T to 1.8T and a curvature radius of 15m. The research findings provide valuable references for the design of drilling tools and drilling operations in slim-hole short-radius horizontal wells.

Keywords: Slim Hole; Short Radius; Passing Ability; Double-Bend Screw Drill

1. Introduction

The hole curvature of short-radius horizontal wells is usually within the range of (30° - 150°) per 30 m, and the curvature radius is between 10 and 60 m. By sidetracking the casing window into this type of well, operators can significantly enhance the extraction of remaining reserves in the near-wellbore area, thereby improving the overall recovery rate. However, the construction of slim-hole short-radius horizontal wells presents a number of challenges, including complicated processes and difficulties associated with sidetracking and pressure application, difficulty in passing through for screw drill. As the curved shell screw drill navigates through the deflection section, it faces considerable obstacles due to the limited annular space between the drill and the well wall, compounded by the large bending angle of the drill. These factors can impede the drill's progress, making effective drilling more complex.

Zhu Xiaohua et al.[1] found that when the structural bending angle is large, the single-bend screw drill needs to be pressurized to pass through the casing. Chen Zuxi et al.[2] analyzed the deformation of the screw drill tripping in the casing based on the principle of minimum deformation energy, and solved the problem of the boundary being determined in the deformation process. Tuo Haiyang et al.[3] considered the influence of parameters such as the effective window length and the motor bending angle, and the analog calculation of screw drill assembly passing through the window was conducted using the finite element analysis software—ABAQUS. The maximum stress and total friction resistance of the screw drill assembly were calculated, and the trip in capacity of the screw drill assembly was determined by the allowable friction resistance and allowable stress. Liu Jvbao et al.[4] studied the passing ability of the bend screw drill for horizontal wells drilled inside the 139.7 mm casing. Sun Jian et al.[5] studied the trip in resistance of a large-angle single-bend screw in a 177.8 mm casing. Li Fuxing et al.[6] Through the optimized design of the wellbore trajectory, the adoption of the section milling and casing window opening method, the selection of the drilling fluid system suitable for this region, the optimization of the types of drill bits and screw drill tools, as well as the implementation of refined construction measures, the technical difficulties in the construction have been solved. WEI Zengjie et al.[7]uses the continuous beam theory to set up a mechanical model to analyze the force and deflection of the bottom hole assembly with double bent housing PDM in 139.7 mm casing, then the friction between the casing and BHA can be calculated. The possibility running PDM with double bent angle into the hole can be determined by comparing the friction with the weight of BHA. In fact, BHA with double bent housing PDM can be successfully run into 139.7 mm casing. CAO Yongbin et al.[8] combines the drill bit, screw, short drill collar, and stabilizer in a fixed order. It has a double stabilizer rigid structure.The main reasons why different drilling tool combination parameters affect wellbore trajectory control are analyzed. SHI Xiao bing et al.[9] based on the solids dynamics finite element theory, a dynamics model of reverse connecting of the double - bent screw drill in the deviated hole is established. The stress field of bottcm hole assembly, and the drill stem strengthis analyzed and evaluated using this model. CHEN Jie et al.[10] introduces the test results of high build-up rate bottom hole assembly through the window of the casing sidetracking and offers suggestions for improving performance of high build-up rate BHA through the window. The aforementioned studies did not analyze the passing ability of the slim-hole short-radius horizontal wells. Considering the characteristics such as small annular space and large bending angle of screw drill, the following conditions should be met to ensure the safe passage of screw drills for slim-hole short-radius horizontal wells:

(1) Geometric condition: The bending deformation in the screw drill assembly should be less than the allowable deformation to ensure the normal operation;

(2) Contact force condition: The contact force exerted by the screw drill against the well wall should be less than the permissible contact stress to prevent accidents;

(3) Strength condition: The working stress of the screw drill is less than the allowable stress to ensure no fracture or breakage;

(4) Friction resistance condition: The axial force of the cross section of the screw drill should be greater than zero to overcome the friction resistance and be tripped in by the the weight of the screw drill.

Currently, there are more studies on the passing ability of single-bend screw drill tools. However, most of the mechanical studies on double-bend screw drill focus on the problem of predicting the build-up rate. As for the passing ability, in field practice, it is usually determined by empirical or experimental methods, resulting in insufficient understanding of mechanical problems. Especially in the case of small-hole and short-radius horizontal wells drilled by sidetracking through casing windows, due to the large hole curvature, the frictional resistance generated by the contact between the double-bend screw drill with large bending angles and the well wall will lead to problems such as a small effective weight on bit, a slower drilling speed, and even the inability to drill, which seriously affects the drilling construction. Therefore, it is necessary to analyze it to provide references for drill tool design and drilling construction.

In this paper, a study on the passing ability of double-bend screw drill of casing window sidetracking into a slim-hole short-radius horizontal well was conducted. The passing ability of screw drill in the casing section was analyzed through modeling. The passing ability of double-bend screw drill in the open-hole section was analyzed through finite element software. The results indicate the weight on bit that is allowed to pass through under different hole curvatures.

2. Theoretical Model

The maximum length of the screw drill assembly that can be smoothly tripped in is affected by the wellbore trajectory, wellbore size and tool diameter. According to the trip in requirements of the screw drill assembly, the total length of the tool is less than the maximum length L allowed to pass through the wellbore. As shown in Figure 1, considering the deformation of the screw drill assembly in the bending and deflection sections, the passing ability of the tool is determined by the following methods.

In general, the screw drill is deformed within the wellbore. Assuming the wellbore curvature radius is R, the wellbore diameter is d_b, the outer diameter of the screw drill is d_{to}, the deformation of the screw drill is y_c, and the length of the screw drill is L, as shown in Figure 1. According to the figure, the general mode for the passing ability of the screw drill assembly can be obtained.

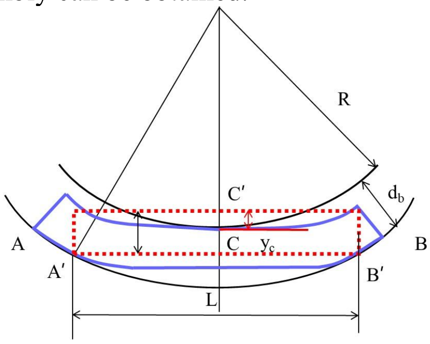

Figure 1. The Passing Ability of the Tool

$$L = 2\sqrt{(R+d_b)^2 - (R+d_{to}-y_c)^2} \quad (1)$$

$$R = \frac{L^2}{8(d_b - d_{to} + y_c)} - \frac{d_b + d_{to} - y_c}{2} \quad (2)$$

Formula (1) and Formula (2) are called general modes. According to Formula (1), the passing ability of the screw drill assembly can be determined with a given wellbore curvature radius. According to Formula (2), the wellbore curvature radius can be designed with given structural parameters of the screw drill. General modes (1) and (2) have the following three conditions:

(1) When $y_c = 0$, that is $L = L_{rc}$, it is called a rigid condition.

(2) When $y_c < 0$, that is $L < L_{rc}$, it is called the gap condition.

(3) When $y_c > 0$, that is $L > L_{rc}$, it is called deformation condition.

Where L_{rc} is the critical length under the rigid condition.

passing ability mode of borehole assembly under the rigid condition:

a. When $y_c = 0$, Formula (1) and Formula (2) become

$$L_{rc} = 2\sqrt{(R+d_b)^2 - (R+d_{to})^2} \quad (3)$$

$$R_{rc} = \frac{L_{rc}^{\ 2}}{8(d_b - d_{to})} - \frac{d_b + d_{to}}{2} \quad (4)$$

When the deformation of the screw drill is not taken into account and the screw drill is considered to be absolutely rigid, the passing ability L_{rc} of the screw drill is only related to the wellbore diameter d_b, the outer diameter d_{to} of the screw drill and the wellbore curvature radius R. Since d_b and d_{to} are both smaller compared to R, L_{rc} is primarily determined by the size of R.

As the screw drill is absolutely limited by its deformation, it is recommended to use the passing ability mode under rigid conditions to calculate L_{rc} and R_{rc}.

b. When $y_c < 0$, that is $L < L_{rc}$, the general mode can be changed to the gap mode.

$$y_c = (R + d_{to}) - \sqrt{(R+d_b)^2 - (L^2/4)} \quad (5)$$

y_c can be determined according to Formula (5). y_c is not only related to R, d_b, d_{to}, but also to the length L of the screw drill. The shorter the L is, the larger **the** gap is.

c. When $y_c > 0$, that is $L > L_{rc}$, Formula (1) is called the deformation mode.

The passing ability L under the deformation mode is not only related to R, d_b, d_{to}, but also to y_c. The larger the y_c is, the longer the L is. The passing ability of the screw drill assembly derived from the deformation mode is obviously greater than the passing ability derived under rigid conditions. For the deformation y_c, its maximum value $y_{c\max}$ should be less than the maximum allowable deformation $[y_c]$ of the screw drill assembly, that is $y_{c\max} < [y_c]$. The deformation y_c is related to the stress condition of the screw drill assembly, so it is necessary to perform stress analysis on the screw drill.

The stress analysis of the screw drill under deformation conditions shows that, when $y_c > 0$, that is $L > L_{rc}$, due to the constraint of the well wall, the screw drill must be subjected to a lateral force N and an axial force P. The two ends of the screw drill may also be subjected to the action of M_A and. M_B Therefore, the screw drill can be regarded as a simply supported beam subjected to longitudinal and transverse bending loads, as shown in Figure 2.

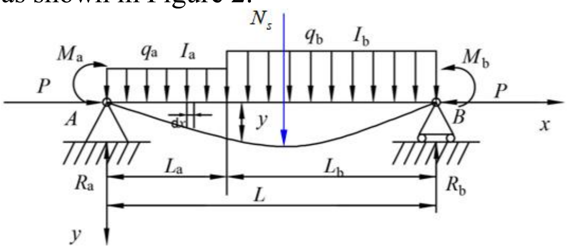

Figure 2. Stress Analysis of Drilling Tool

Relationship between N and L: Assuming $M_a = M_b = m_o$, $K=\sqrt{P/EI}$ $u=KL/2$, by analyzing the longitudinal and transverse bending method of the downhole screw drill assembly based on the mechanical model, we can obtain

$$N=\frac{48EI}{K_nL^3}\left[(R+d_{to})-\sqrt{(R+d_b)^2-(L^2/4)}-\frac{m_oL^2}{4EI}K_m-\frac{5qL^4}{384EI}K_q\right] \quad (6)$$

When $N=0$, $L=L_{dc}$, L_{dc} is the critical length of the passing ability under deformation conditions, and the L_{dc} equation is as follows

$$(R+d_{to})-\sqrt{(R+d_b)^2-(L_{dc}{}^2/4)}-\frac{m_oL_{dc}{}^2}{4EI}K_m-\frac{5qL_{dc}{}^4}{384EI}K_q=0 \quad (7)$$

Where

$$K_m = (\sec u - 1)/u^2$$

$$K_n = 3(\mathrm{tg}u - u)/u^3$$

$$K_q = 24(\sec u - 1 - u^2/2)/5u^4$$

$$q = W\sin\alpha K_f, K_f = 1-\gamma_m/\gamma_s$$

Unit length weight of drilling tool W, kg/m; Deviation angle α, degree; Buoyancy factor K_f; Density of drilling fluid and drill steel γ_m, γ_s, g/cm^3; Stiffness EI, kg/cm^2.

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The bending angle mode for the maximum passing ability of the screw drill assembly under rigid conditions is defined as follows: the wellbore curvature radius is R, the wellbore diameter is d_b , the outer diameter of the screw drill is d_{to} , L_{rc} is the critical length of the screw drill under rigid conditions, representing the maximum passing ability, and γ_c is the critical bending angle. According to the model shown in Figure 3, the following Formula (9) can be derived, which is referred to as the critical bending angle mode:

$$\gamma_c = 2\sqrt{1-(\frac{R+d_{to}}{R+d_b})^2} \quad (8)$$

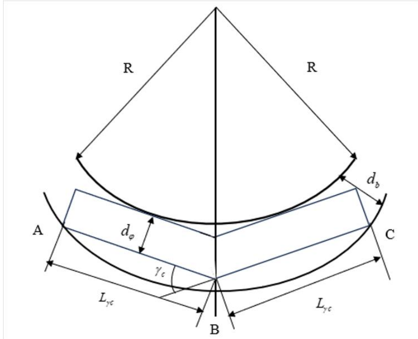


Figure 3. Bending Angle Mode Diagram of Drilling Tool

The critical bending angle γ_c is only related to R, d_b and d_{to} . When R, d_b and d_{to} are fixed, γ_c is a constant. In a hinged drilling tool assembly for a horizontal well with a short curvature radius, the movable bending angle of the hinge joint should be within the lower limit γ_c , representing $\gamma \geq \gamma_c$.

3. Analysis on the Passing Ability of Double-Bend Screw Drill

3.1 Casing Passing Ability

The previous analysis of drilling tool passing ability indicates that the conditions for determining the screw passing ability include: geometric conditions, contact force conditions, strength conditions, and friction resistance conditions. It is related to the inner diameter of the drill pipe, the diameter and curvature of the wellbore, the bending angle and length of the screw, the position of the bending point and the size of the drill bit.

The following basic assumptions are made in the process of tubular string lowering: a. The lowering tool is a homogeneous beam constrained by the wellbore; b. The wellbore is rigid; c. The contact is point contact. In order to solve the problem of the drill string passing through the casing, it is necessary to solve the lateral force exerted on the drilling tool by the casing when the drill string transitions from its free state to its deformed state. Therefore, it is first necessary to calculate the displacement of the bending point in the free state and determine whether this displacement exceeds the inner diameter of the casing. If it does exceed the inner diameter, it is necessary to solve for the displacement of the constraint point after deformation. As shown in the Figure 4, the displacement of the constraint point is derived from a geometric analysis of the double-bend screw drill. The displacement of the constraint point is derived from a geometric analysis of the double-bend screw drill. Table 1 lists the dimensional design and geometric analysis results of the passability for a 73 mm double-bend motor based on the aforementioned tubular passability formula.

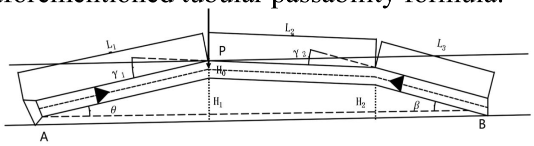


Figure. 4 Schematic Diagram of the Double-Bend Screw Drill Passing through the Casing Section

Table 1. Calculation Results from Geometric Analysis

Name	Unit	Number
Outer diameter of drill pipe (H_0)	(mm)	73
Inner diameter of casing (D)	(mm)	124.26
Lower bend angle (γ_1)	(°)	3
Upper bend angle (γ_2)	(°)	1.5
Initial span length (L_1)	(m)	0.93
Distance between two bend points (L_2)	(m)	2
Termination distance (L_3)	(m)	1.6
Displacement of lower bend point (H_1)	(mm)	47.3
Result		Pass

As shown in the result mentioned above, the displacement H1 at the lower bend point is larger than the displacement H2 at the upper bend point of the constraint point. Therefore, the passing ability at the lower bend point is mainly considered. Since H0+H1=L=120.3mm ＜ D=124.26mm, it is considered that the double-bend screw drill can pass smoothly without deformation.

3.2 The Passing Ability of the Lower Open Hole Section

(1) Geometric condition: The maximum allowable length L=3.29m＞L_1, L_2, L_3, which meets the requirements; the critical bending angle γ_c=2.05°＜the lower bend angle γ_1=3° under rigid conditions, and the passage under deformation conditions needs to be considered.

(2) Strength condition:

When the double-bend positive displacement motor (PDM) passes through the open-hole section, it must meet the strength requirements, that is, the working stress must be less than the allowable stress. This means that during the process of running the drill string, the combined stresses such as bending stress and axial force experienced by the PDM must not exceed the allowable stress of the material; otherwise, it may lead to the breakage or damage of the PDM. Table 2 provides the mechanical properties of the commonly used 73 mm double-bend positive displacement motor (PDM), which serve as the fundamental parameters for the subsequent numerical simulation.

Table 2. Calculation Results of Bending Strength for Double-bend Screw Drill

Dimension (mm)	73
Material	35GrMo
Minimum yield strength/MPa	835
Safety factor	1.15
Maximum stress of body/MPa	245.1
Maximum stress of joint/MPa	612.75
Body safety factor	3.41
Joint safety factor	1.36

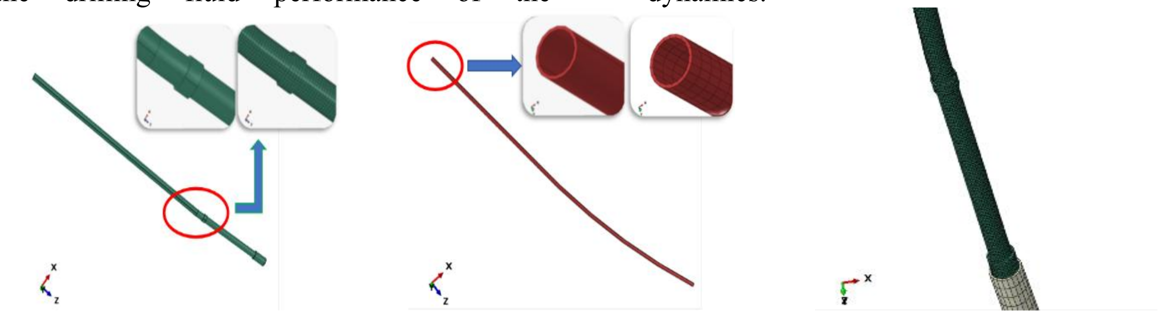
(3) Friction condition: numerical simulation was used, and the simulation method and results are as follows:

ABAQUS software was used to simulate the passing ability under different curvature radii and different weight on bit as boundary conditions. The curvature radius were set at 30m, 20m, and 15m, respectively. The specific boundary conditions are shown in Table 3.

Table 3. Boundary Conditions for Double-bend Screw Drill

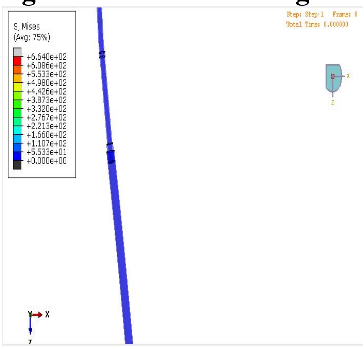
Item	weight on bit(WOB)	Curvature radius
1	1.0T	30m
2	1.0T	20m
3	1.0T	15m
4	1.5T	30m
5	1.5T	20m
6	1.5T	15m
7	1.8T	30m
8	1.8T	20m
9	1.8T	15m
10	2.5T	30m
11	2.5T	20m
12	2.5T	15m
13	3.0T	30m
14	3.0T	20m
15	3.0T	15m

The model and mesh division were established according to the relevant parameters of the double-bend screw drill and the actual wellbore trajectory. As shown in Figure 5, the double-bend screw drill and the wellbore trajectory were placed in a plane. Boundary condition setting: fixed constraints were set on the outside of the wellbore, with the outer surface of the drill string in friction contact with the inner wall of the wellbore. Based on the drilling fluid performance of the sidetracking well, the friction coefficient was set to 0.25. The drill string model was lowered into the wellbore, the pressure was applied to the cross section of the drill string, and the calculation was performed using explicit dynamics.

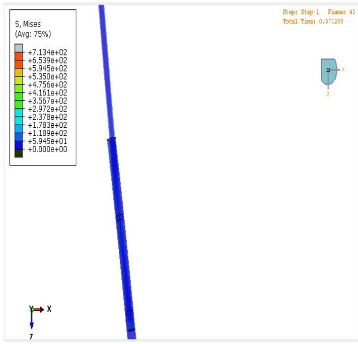


a. Drill Bit+Double - Bend Screw Drill Mod **b. Wellbore Model** **c. Double-Bend Screw Drill and Wellbore Matching**

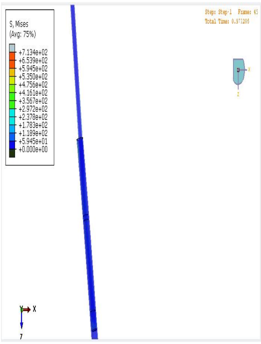
Figure 5. Schematic Diagram of the Stress State of the Double-Bend Screw Drill



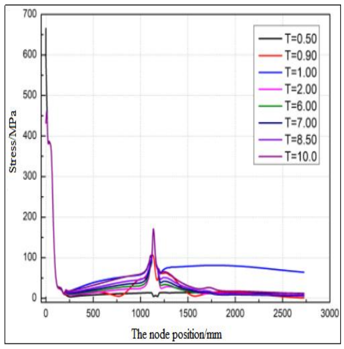
a. 1T



b. 1.5T



c. 2.5T



d. Stress at each node position

Figure 6. Simulation Results for the First Section of the Wellbore Passing Ability using the Double-bend Screw Drill

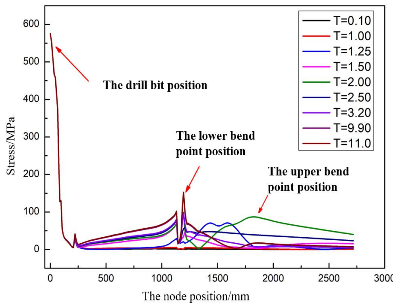
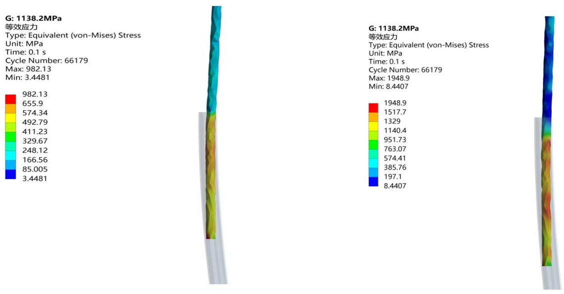


Figure 7. Stress Values for the Second Section of the Wellbore Passing Ability Using the Double-bend Screw Drill



a. 3T, curvature radiu 20m **b. 2.5T, curvature radiu 15m**

Figure 8. Simulation Results of Double-bend Screw Drill Failing to Pass the Wellbore under Different Factors

Figures 6 and 7 illustrate that the stress value at the position node, extracted upward along the drilling tool, shows that large stress is generated when the drill bit initially trips in the deflection section, and then the stress is partially reduced. Due to the structural characteristics of the double-bend screw drill with a lower bend angle greater than the upper bend angle, the overall stress on the screw is large when it contacts the well wall at the lower bend angle. However, when it is tripped in thoroughly, the stress on the tubular string decreases to a certain extent.

Overall conclusions: (1)The overall stress on the screw is large when it is initially tripped in at the lower bend angle, and then decreases to a certain extent after it is tripped in completely (the beginning is the most difficult). (2)As the lowering progresses, the contact force and friction force continue to increase, and the increase of friction force is higher than that of normal contact force. The maximum stress value is 754MPa at the drill bit. For a curvature radius of 30m, the double-bend screw drill can be tripped in safely under various weight on bit. When the weight on bit reaches 3T and the curvature radius is 20m, the friction resistance of the tubular string is greater than the axial force due to the contact stress with the well wall reaching 982.1MPa, causing the double-bend screw drill to become severely deformed and unable to pass through the lower bend point smoothly. For a curvature radius of 15m, when the weight on bit exceeds 2.5T, the contact stress with the well wall reaches 1948.9 MPa, preventing the double-bend screw drill from passing through normally, as shown in Figure 8.

To sum up, the double-bend screw drill can be tripped in smoothly and safely under the weight on bit ranging from 1T to 3T and a curvature radius of 30m.

The double-bend screw drill can be tripped in smoothly and safely under the weight on bit ranging from 1T to 2.5T and a curvature radius of 20m.

The double-bend screw drill can be tripped in smoothly and safely under the weight on bit ranging from 1T to 1.8T and a curvature radius of 15m.

4. Conclusion

The 3°-1.5° double-bend screw drill tools can be allowed to pass through the cased hole section. The weight on bit that is allowed to pass through the open-hole section is related to the hole curvature. Reasonably designing the structure of the double-bend screw drill and the construction parameters can reduce the resistance when the screw drill pass through. The properties of drilling fluid, especially its impact on the friction coefficient, have a significant influence on the passing ability of screw drill tools. In this paper, the friction coefficient is a fixed value. The hydrodynamic effects in the drilling were not considered, the drilling fluid generates an axial force, which increases the double-bend screw drill's passing ability. n order to guide the actual construction, it is expected to conduct further research on the influence of the properties of drilling fluid on the passing ability of screw drill.

In this finite element analysis, the forces acting on the screw drill tools were simplified. The focus was on analyzing the axial forces of the screw drill tools, and whether they could pass through was judged according to the axial forces. In future studies, the influence of torque on the passing ability can be included.

Suggesting future research directions, particularly for validating these findings experimentally or applying them to various well geometries and drilling conditions.

5. Credit Author Statement

Xugang Liu: Writing - Original Draft; Hui Zhang: Conceptualization; Zhanmiao Yu: Supervision; Yongchao Feng: Data Curation; Dalei Li:Data Analysis ;Changjin Wang: Formal Analysis; Jiaqin Liu: Numerical Simulation; Changhao Wang: Simulation, Writing - Review & Editing.

6. Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Acknowledgements

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