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Passability test and simulation of sand control string with natural gas hydrates completion in large curvature hole

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A B S T R A C T

To meet the requirements of marine natural gas hydrate exploitation, it is necessary to improve the penetration of completion sand control string in the large curvature borehole. In this study, large curvature test wells were selected to carry out the running test of sand control string with pre-packed screen. Meanwhile, the running simulation was performed by using the Landmark software. The results show that the sand control packer and screen can be run smoothly in the wellbore with a dogleg angle of more than 20°/30 m and keep the structure stable. Additionally, the comprehensive friction coefficient is 0.4, under which and the simulation shows that the sand control string for hydrate exploitation can be run smoothly. These findings have important guiding significance for running the completion sand control string in natural gas hydrate exploitation.

1. Introduction

Sand production from natural gas hydrate exploitation borehole is one of the bottlenecks that restrict the safe and efficient exploitation of natural gas hydrate (Lu JS et al., 2020; Ding JP et al., 2019). To solve this problem, gravel packing and sand control screen liner running are needed in the wellbore (Calderon A et al., 2008). In recent years, the trial production of natural gas hydrate in the sea area in China has adopted the horizontal well structure (Ye JL et al., 2020), which makes it difficult for sand control string running in the long horizontal wellbore with large curvature. If the sand control string is not run in place or the running process is damaged, it may cause sand control failure and lead to an early shut-in. Therefore, it is very important and necessary to carry out the passability verification and numerical analysis of sand control string in large curvature borehole, improve the string running measures and enhance the success rate of sand control string running.

The existing research on string running mainly focuses on the fields of casing and fracturing string, and the commonly used research methods include numerical simulation, theoretical analysis, and test. Through the theoretical analysis and experiments, the formula of the maximum borehole curvature through which the casing can pass (Li JS et al., 2018) and the formula of the length of a single hole under the constraint of the elastic model are obtained (Chen YC et al., 2019). The axial force of fracturing string, the lateral force of string, the friction force between string and borehole wall, the self-locking of string, the maximum bending degree of string, and the maximum dogleg degree of the borehole are compared. In this way, the constraint formula is obtained and then applied to guide the production practice (Zhang L et al., 2011). The research methods of string running are

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summarized into the analytical method, energy method, and finite element method (Gao DL and Huang WJ, 2021; Liu QK et al., 2016).

In the study of sand control string passability, ANSYS finite element analysis software is used to disperse the inner and outer strings into beam elements for simulation calculation, and it is concluded that when the borehole curvature is more than 10°/30 m, the bending stress accounts for more than 1/2 of the equivalent stress (Xu J et al., 2017). The outside diameter of the flexible screen liner without plastic buckling is simulated and optimized by using Landmark well plan software (Bi YS et al., 2019). It is proposed to combine the finite element analysis with practice to define the application of horizontal well completion string running in the oilfield (Wang Q et al., 2017). Combining with the actual phenomenon, the paper analyzes the sticking reasons for sand control string running in multilateral horizontal wells, and considers that the early opening of the packer, sundries in the wellbore, and too small gap of string are the reasons leading to difficult running (Li J et al., 2020; Cai QJ et al., 1998). Through a further study on the influence of sand control packer on string running, it is suggested that due to the trajectory during running, the packer's running against the edge and the packer slips' collision with the casing coupling gap cause pin shearing and partial opening of the slips, thus resulting in the blockage of sand control string in large curvature wells (Cheng F, 2020; Zhang HW, 2014). In addition, research on multifunctional sand control string has been carried out (Luo YH and Wang WD, 2021). The existing research pays attention to the analysis of the mechanical properties of the string, but the research on the influence of the multi-layer structure of sand control string on the complex structure wells is insufficient, and the possible differences between practice and theory are ignored (Shaibu R et al., 2021; Lin Y et al., 2022; Cai JC et al., 2020).

Therefore, Landmark software is used to simulate the running of the sand control string, and the analysis and simulation are carried out, to comprehensively evaluate the running feasibility of the new-typed sand control packer and screen liner. The optimized sand control string is successfully run down to the set depth, which is of great significance to feasibility and safety guidelines of the shallow dogleg well completion and has good promotion and application value.

2. Technical difficulties of sand control string running in large curvature borehole

To deal with the problem of sand production in the process of hydrate reservoir exploitation, the mode of gravel packing + screen liner completion is often used. During the gravel packing operation, it is necessary to place a layer of wash pipe in the screen liner as the return channel of the gravel-carrying fluid. Generally, the structure of sand control string from top to bottom is drill pipe + sand control packer + screen liner (including wash pipe) + guide shoe.

When the double-layer sand control string passes through the large curvature and horizontal section, there are the following technical difficulties:

(i) The internal and external double-layer string structure increases the line weight of the sand control string. Generally, the composite line weight of 5-1/2 ″ pre-packed screen liner + 4 ″ wash pipe is close to 100 kg/m. The packer and the screen liner are located at the lowest part of the sand control string. After entering the horizontal borehole, this section basically has no effect on the increase of the axial downward pressure but will increase the friction with the inner wall of the casing, thus resulting in the deformation and damage of the outer sheath of the screen liner from sliding friction, and the hindrance of string running.

(ii) The overall rigidity of sand control double-layer string structure is strengthened, and it is more difficult to adapt to the borehole structure in the large curvature well section, which may make it stuck in the bending section of the borehole and unable to run in, or cause the cross-section of the string body to deform into an ellipse, reduce the drift diameter of the string and affect the subsequent operation.

(iii) After the completion casing is perforated, it is very easy to form sand settling in the casing, and it is difficult to thoroughly clean the borehole even if the thick plug is circulated many times. The pre-packing screen generally adopts a bridge-type outer sheath, and the surface of the outer sheath is uneven, so that formation sand is entrained and carried to migrate in the horizontal wellbore, the friction increases, and the risk of sand sticking is aggravated.

(iv) When the sand control packer assembly and the packing tool assembly pass through the large curvature section, they will collide and scrape with the casing coupling gap, and they will be bending for a long time in this process, which will affect the stability of the sand control packer and the packing tool assembly, and may lead to a series of complex situations such as the normal setting failure or the sealing failure of the sand control packer.

3. Sand control string running in a large curvature borehole

3.1. Force analysis of sand control string running

3.1.1. Comprehensive friction in the wellbore of the sand control string

To prevent the sand control packer from being set in advance due to rotation in the process of running, it is strictly prohibited to rotate the sand control string, so the torque value is set as 0. Because the sand control string is lifted and lowered at a uniform speed in the test, the suction force of the string is not considered. In the process of lifting and lowering the string, the resistances include: (1) The friction resistance between the sand control string and the casing; (2) additional resistance caused by the bending moment when the sand control string is rigid in contact with the casing. The combination of the two is the total friction of sand control string in the wellbore (Liang QM et al., 2019).

$$G\cos\alpha = F_f + F_{bd}\cos\alpha + F_{hl} \tag{3-1}$$

$$F_f = G\cos\alpha - F_{bd}\cos\alpha - F_{hl} \tag{3-2}$$

When the string is lifted at a uniform speed, the hook provides a lifting force F_{hl}, and the effective component of gravity is in the same direction as the total friction F_f (3-1, 3-2), as shown in Fig. 1:

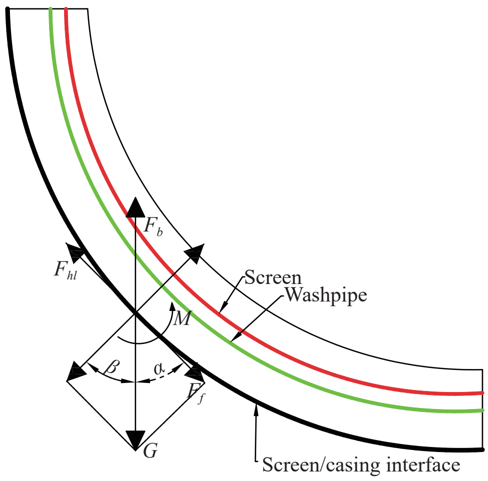

Fig. 1. Force analysis of sand control string lifting.

$$F'_{hl} = G\cos\alpha + F_f - F_{bu}\cos\alpha \tag{3-3}$$

$$F_f = F'_{hl} - G\cos\alpha + F_{bu}\cos\alpha \tag{3-4}$$

By adding 3-2 and 3-4, the following solution equation of F_f could be obtained 3-5:

$$F_f = \frac{F'_{hl} - F_{hl}}{2} \tag{3-5}$$

3.1.2. Optimized friction calculation method

Landmark well plan module cannot get the friction coefficient through the inversion of the experimental hook load data, but can only simulate the string hook load under different friction coefficients, and gradually fit with the experimental hook load to get the friction coefficient close to the real value.

The calculation equation of the axial force for the string unit is obtained by taking the whole string as a soft rod model without considering the lifting and lowering torque of the sand control string (Yan T et al., 2011) 3-6–3-8:

$$T_{i+1} = T_i + \left(W_g dl\cos\alpha \pm \mu N_i\right) \tag{3-6}$$

$$N_i = \sqrt{(T_i\Delta\phi\sin\alpha)^2 + \left(T_i\Delta\alpha + W_g dl\sin\alpha\right)^2} \tag{3-7}$$

$$F = \pm\mu N_i \tag{3-8}$$

This set of equations is the basis for the software to analyze the friction of string running, where T_{i+1} and T_i are the axial stresses at the upper and lower ends of the ith drill string unit respectively; N_i is the positive contact pressure between the ith drill string unit and the borehole wall; W_g is the buoyant weight of the drill string per unit length; μ is the coefficient of sliding friction; F is frictional resistance; α, $\Delta\alpha$ and Δ are the average deviation angle, deviation angle increment, and azimuth angle increment, respectively, which are taken as "+" when the drill string moves upward and "−" when the drill string moves downward.

3.2. Sand control string passability test

In view of the shallow burial and non-diagenetic characteristics of hydrate formation, the exploitation of natural gas hydrate needs to adopt the design of large curvature and long horizontal section, or employ the complex two-dimensional trajectory. A well with a maximum hole build-up rate of more than 20°/30 m is selected to conduct a sand control string passability test.

Fig. 2 shows that the hole build-up rate of the first build-up section of the well is more than 20°/30 m, the hole build-up rate of the second build-up section is more than 10°/30 m, and the inclination angle of the toe section is reduced, which makes the whole hole in an "S" shape and further increases the difficulty of sand control string running.

Because there are many liquid impurities in the wellbore, which will adversely affect the sand control effect of the screen liner, with the cost and test effect taken into consideration, the partial 5-1/2″ pre-packing screen liner in sand control string is replaced by a 7″ blind string with similar line weight. The structure of the sand control string from top to bottom is as follows: 4-1/2″ drill pipe + sand control packer + 5-1/2″ screen liner + 7″ blind pipe + 5-1/2″ screen liner + 5-1/1″ guide shoe, shown in Fig. 3.

Sand control string running test has been carried out two times, as shown in Fig. 4. After running the sand control

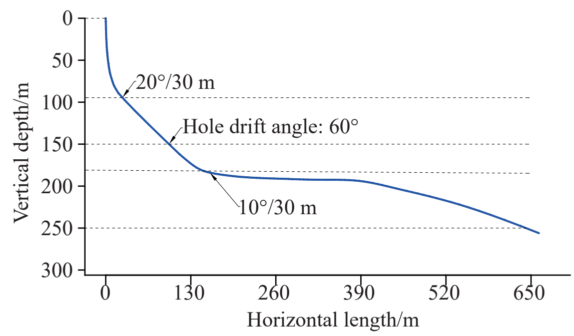

Fig. 2. Borehole trajectory diagram of test well.

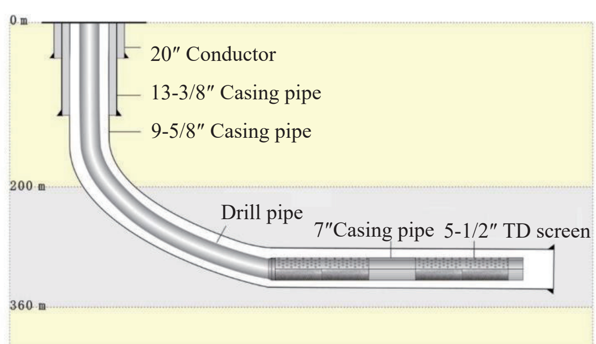

Fig. 3. Schematic diagram of sand control string structure.

string for the first time, the whole sand control string is taken out when the drill pipe trial pressure is set up at 30 MPa, which costs 10 days. After the sand control packer is replaced for the second time, the sand control string is run in as a whole, the packer is set mechanically, and the string is taken out and sent in after being released. In both tests, the sand control string has been placed in the well for 3 days and 1 year, respectively, in order to test the effect of different soaking times on-screen liner subjected to bending stress.

The two tests of lifting and lowering sand control string are successful without obvious blockage and sticking, and the string is lowered by its weight, which indicates that the screen liner has a good passability in the vertical, large dogleg, and horizontal sections. The removed screen liner has no obvious deformation damage such as extrusion and distortion, only slight scratches on the surface, and is only affected by the complex liquid in the well after entering the well for the second time. The surface is darkened with a dirty layer, but it does not have a substantial impact on the sand control ability of the screen liner, as shown in Fig. 5. The total friction curve of the sand control string is obtained after the hook load data in the test is calculated by Equation 3-5, shown in Fig. 6.

It can be seen that within 300 m, the sand control string is passing through the build-up section, and the friction increases linearly with depth. Below 300 m, when the sand control string enters the horizontal section, the string shape is relatively stable, at this time, the increase in friction is obtained not only from the sliding friction between the screen liner and the inner wall of the casing, but also from the additional friction caused by the bending moment of the string in the whole build-up section, and the increasing trend is gradually strengthened. When the string reaches the bottom of the well, the maximum friction value is 6.8 T. The piecewise fitting functions are as follows Equation 3-7–3-10:

Above 300 m：

$$y_f = 0.00717x_{\text{depth}} + 0.41763 \tag{3-9}$$

below 300 m：

$$y_f = 0.01297x_{\text{depth}} - 1.51213 \tag{3-10}$$

It is found by fitting that the increasing trend of friction is slower when the buried depth of pipe is shallower than 300 m (slope 0.00717 < 0.01297), which indicates that the increasing effect of sliding friction on the total friction in the horizontal section is higher than that in the deflecting section after the pipe passes through the deflecting section. Therefore, as far as

Fig. 4. Screen liner before being run into well and screen liner being run into well.

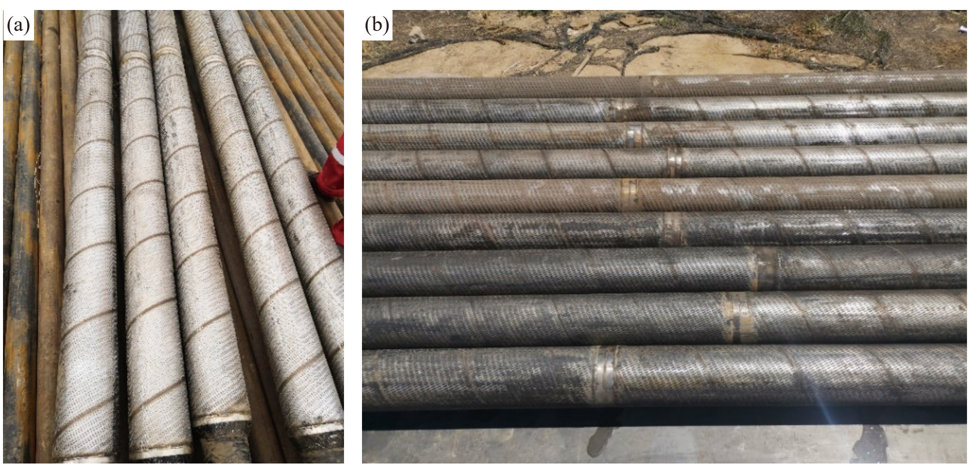

Fig. 5. Scratches on screen liner after it comes out of the well. a–screen liner taken out immediately after entry; b–screen liner taken out one year after entry.

the effect of the high build-up section of the test well on the friction coefficient is concerned, different friction coefficients are set according to the upper and lower build-up sections of the casing section. The screen model of the Landmark well plan module is used to set the simulation parameters of the sand control string and carry out the string tripping simulation. The results are shown in Table. 1 and Figs. 7–10. In the fitting curve, running-in represents F_{hl} in Equation 3-5, and pulling-out represents F_{hl} in Equation 3-5.

The simulation results show that: (1) The fitting degree of sectional friction is good; (2) the friction of the upper high build-up section in the casing is higher than that of the lower low build-up section; (3) the running friction coefficient of sand control string is 0.5–0.7 in the high build-up section of the casing, and 0.3 in the steady angle section and horizontal section of the casing; (4) the lifting friction coefficient of the sand control string is 0.5 to 0.7 in the high build-up section of the casing, and 0.3 in the steady angle section and horizontal section of the casing; (5) the friction coefficient of the open hole is 0.35–0.40.

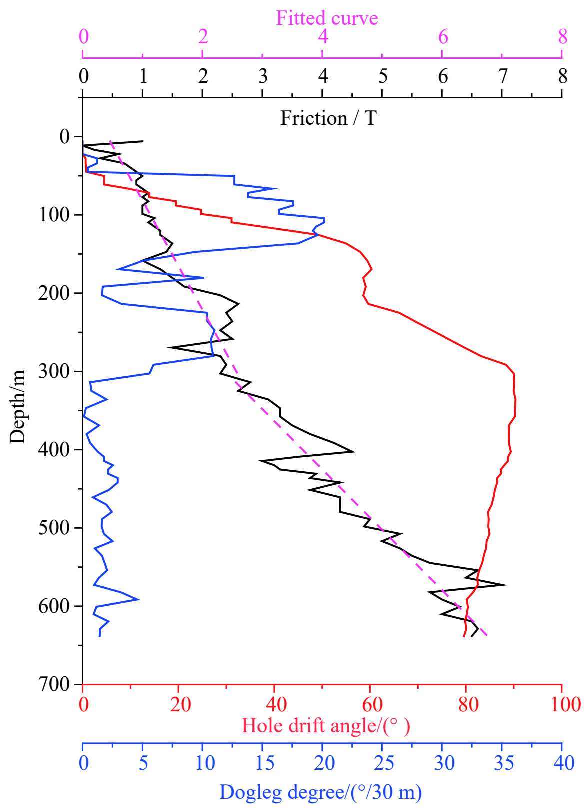

Fig. 6. Sand control string friction and test borehole data.

Table 1. Friction analysis of sand control string.

Operating condition			Down-pass	Lifting
Calculating parameter	Fitting results of friction coefficient	High deflection casing section	0.5–0.7	0.5–0.7
		Steady slope section + horizontal section casing	0.3	0.3
		In the open hole	0.40	0.35
	Tripping speed /(s/m)		10–20	10–20

It can be seen from Fig. 10 that the friction range of the lifting and lowering of the sand control string is within 8 T, which is close to the friction value of 6.8 T obtained from the test. The average friction coefficient of this type of sand control string running in the casing is 0.4.

3.3. Numerical simulation analysis

Based on Equation 3-6– 3-10, combined with the exploitation characteristics of hydrate reservoirs in the South China Sea, the hook load simulation of sand control string in hydrate exploitation wells in the sea area is carried out, which provides a reference for subsequent studies. In the conventional oil and gas industry, the friction coefficient of carbon steel and carbon steel is generally taken as 0.25, and according to the friction coefficient fitting results obtained from the test wells, the software input friction coefficients are determined to be 0.25 and 0.4, respectively. The running string structure of the simulated production well is 5-7/8 "conventional drill pipe + 5-7/8" weighted drill pipe + variable thread + 5-1/2 "drill pipe + variable thread + sand control string (including wash pipe) + double valve guide shoe. The results are as follows:

(i) Tripping analysis when friction coefficient being 0.25.

The simulation results are shown in Fig. 11, and the hook load is substituted into Equation 3-5 to obtain Fig. 12.

Fig. 12 shows that the friction increases with the increase of running depth in the process of the sand control string running, and reaches the maximum at the bottom of the well, the friction value of 12 T.

(ii) Tripping analysis when friction coefficient being 0.4.

The simulation results are shown in Fig. 13, and the hook load is substituted into Equation 3-5 to obtain Fig. 14.

It can be seen from Fig. 14 that when the friction coefficient is 0.4, the maximum friction value of the sand control string running at the bottom of the well is 23 T, and the ground hook load is 4.8 T, which is close to two times of the maximum hook load of 12 T when the friction coefficient is 0.25, thus indicating that the increase of friction value will be aggravated with the increase of friction coefficient. This is consistent with the conclusions of the experimental fitting results of Equation 3-9 and Equation 3-10. According to the comprehensive mechanical property test results of the new-typed bypass pre-packing screen liner (Ye JL et al., 2020; Shi HX et al., 2020), the weakest area of the screen liner is the weld between the bridge outer sheath and the weld plate, and the minimum failure tension is 60 T. However, the friction does not act on the screen liner in the form of concentrated force but is the integral resultant force of the friction of sand control string running in the casing, and the maximum friction of 23 T is far from reaching the minimum limit value of screen damage. Therefore, it is believed that the sand control string can be smoothly lowered to the design position in a clean horizontal well for hydrate exploitation.

The practice shows that the optimized sand control string can be put in place once in the well, which plays an important role in the establishment of the sand control system.

4. Discussion

4.1. Problem with lubricant

Whether the use of lubricant is conducive to sand control string running needs to be verified. At present, the commonly used lubricants are solid and liquid. Solid lubricants include plastic pellets (polytetrafluoroethylene), glass beads, graphite, talc, etc. When used, these lubricants can squeeze and rub each other between the bridge outer sheath (uneven surface) of the screen liner and the inner wall of the casing, and there is a risk of blockage. Liquid lubricants include polyalcohol, oxidized polyethylene wax emulsion, polyethylene wax emulsion, etc. Due to high viscosity, liquid lubricants adhere to the wall of the sand retaining layer of the screen liner, affecting the permeability of the screen liner and sand control effect. Therefore, it is necessary to research the effect of lubricants on sand control string running.

4.2. Problems with simulation software

Commonly used string mechanics simulation softwares, such as ANSYS, Landmark, etc., do not have a special simulation module for sand control string running, especially for the double-layer pipe structure with outer screen and inner wash pipe. Widely used at present, that structure can only be simplified into a single-layer structure by line weight to carry out the simulation, and the stress complexity of the double-layer string structure in the well is far more than that of the single-layer string. In addition, compared with drill pipe, casing, and other pipes, the structure of the screen liner is more complex and has more weak points. Therefore, it is

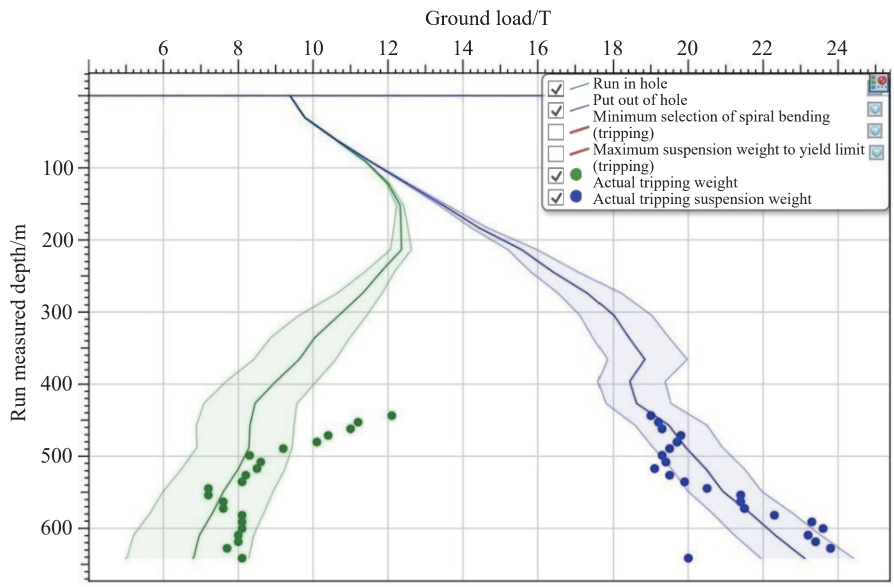

Fig. 7. Fitting of simulated friction and actual friction of 9-5/8 "casing section of sand control string.

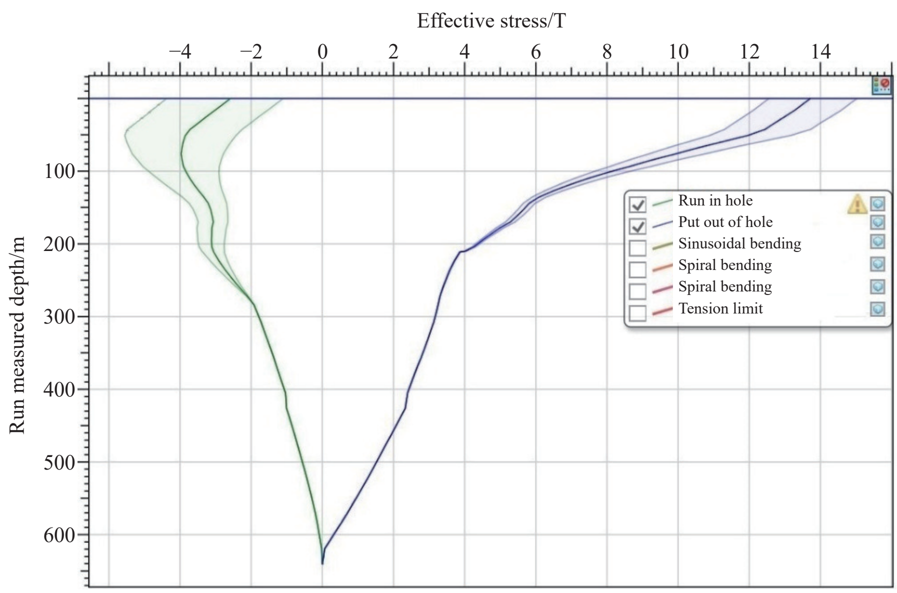

Fig. 8. Calculation results of effective axial stress during tripping of the sand control string.

necessary to develop a program suitable for sand control string running simulation based on existing modules.

4.3. Problems with sand control packer

Sand control packer and packing assembly have many matching mechanisms and sealing surfaces, and it is difficult to ensure the structural stability of the tool under the action of alternating forces such as bending and extrusion for a long time when passing through a large curvature borehole, so the failure of sand control packer or packing tool occurs from time to time in horizontal wells of oil and gas industry, which hurts the completion sand control operation. So, it is necessary to optimize the structure and material of common sand control packer and packing assembly tools to improve the reliability of the tools after passing through the large curvature borehole.

4.4. Problem with sand accumulation in the wellbore

After the casing is opened, the formation sand flows into the wellbore, and when the completion sand control string is run in a non-rotational mode, it is easy to cause the formation sand to gradually slip and accumulate with the running of the sand control string, which is very easy to cause blockage. However, flushing while drilling will aggravate the leakage of completion fluid in shallow soft formation, which is not conducive to the later filling construction. Therefore, it would be a key research question how to effectively solve the problem of shaft sand settling to ensure the smooth running of the string.

4.5. Problems with inverted string

The gravity center of the string can be moved up by the inverted string to increase the axial component force of the string and improve the ability of the string to run by its weight. But there is an optimal value for the length and position of the inverted string. It is necessary to simulate and couple different string structures before construction, and get the best length and position of the inverted string to improve

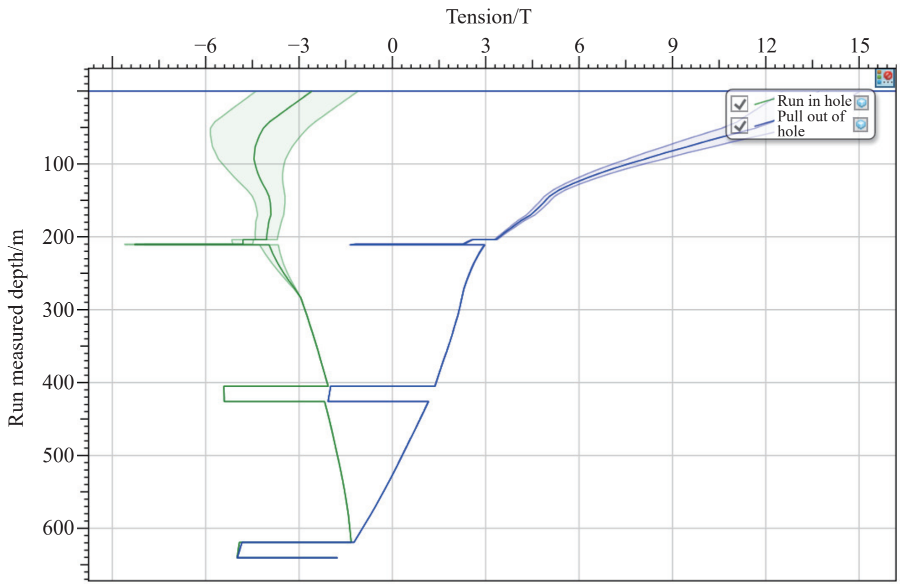

Fig. 9. Calculation results of effective pulling force during tripping of the sand control string.

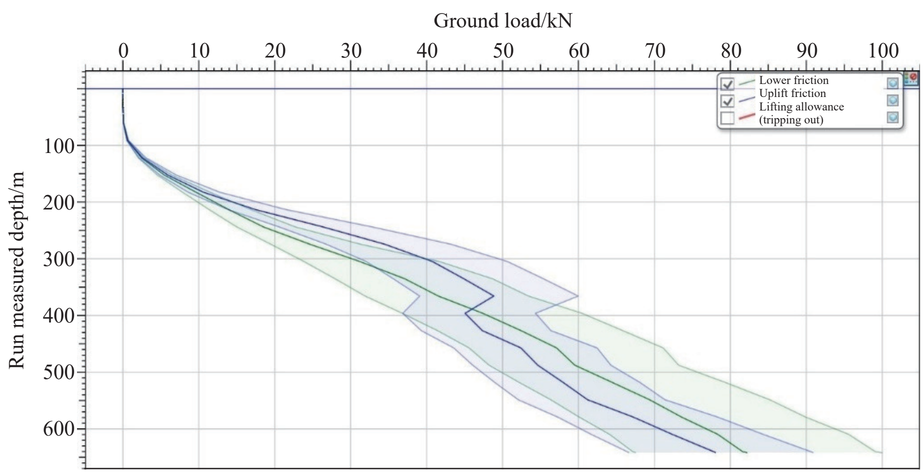

Fig. 10. Calculation results of friction during tripping of the sand control string.

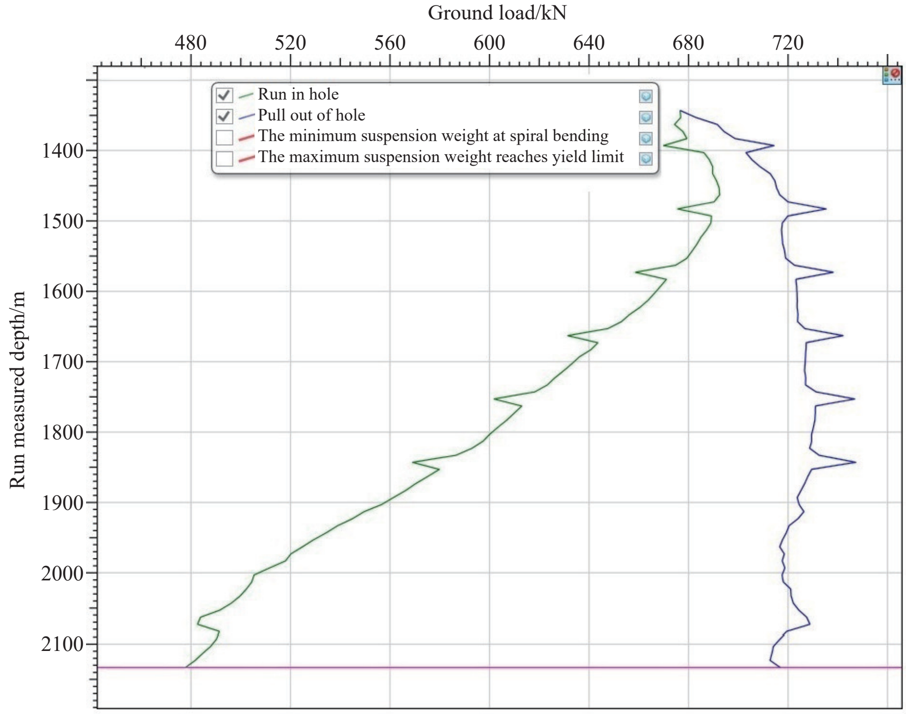

Fig. 11. Change of hook load of sand control string with depth when the friction coefficient being 0.25.

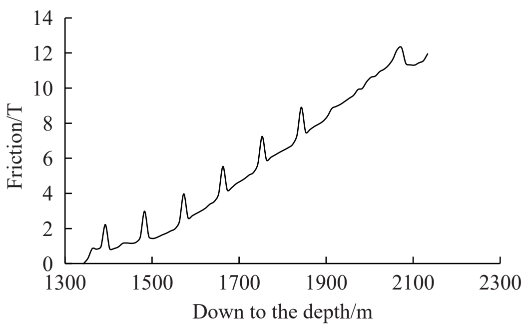

Fig. 12. Friction curve of sand control string running with a friction coefficient of 0.25.

the success rate of string running.

5. Conclusions

The main findings of this study are as follows:

(i) For the well section with a large hole curvature change, the friction will increase with the increase of friction coefficient in a linear trend, so for the horizontal well with large hole curvature, the smooth hole trajectory and stable dogleg degree should be maintained to control the friction coefficient and to reduce the difficulty of sand control string running.

(ii) The sand control string has a combined friction factor of up to 0.4 in the wellbore over 20°/30 m dogleg. However, practice shows that when the length of the horizontal section is not more than 300 m, the well can still be run by its weight without providing additional downforce, and the overall structure of the string can be kept stable.

(iii) Risk assessment of sand control string running in the long horizontal section under complex working conditions needs to use a statistical method to quantitatively or qualitatively analyze the influence of factors such as double-layer string clearance, sand control packer, borehole curvature, lubricant, centralizer and inverted string based on test and simulation. Additional, with the consideration of the measured data and the comprehensive risk evaluation of sand control string running, a reasonable sand control string and related supporting technical measures are determined finally, which provides a reference for field construction and ensures that the sand control string can be run to the preplanned well depth at one time.

CRediT authorship contribution statement

Hao-xian Shi, Yan-jiang Yu, Ru-lei Qin, Jun-yu Deng, Yi-xin Zhong conceived of the presented idea. Hao-xian Shi, Li-qiang Qi, Bin Li, Bo Fan, Qiu-ping Lu, Jian Wang, Kui-wei Li, Ye-cheng Gan, Gen-long Chen, Hao-wen Chen, Zhi-ming Wu carried out the experiment. All authors discussed the results and contributed to the final manuscript.

Declaration of competing interest

The authors declare no conflicts of interest.

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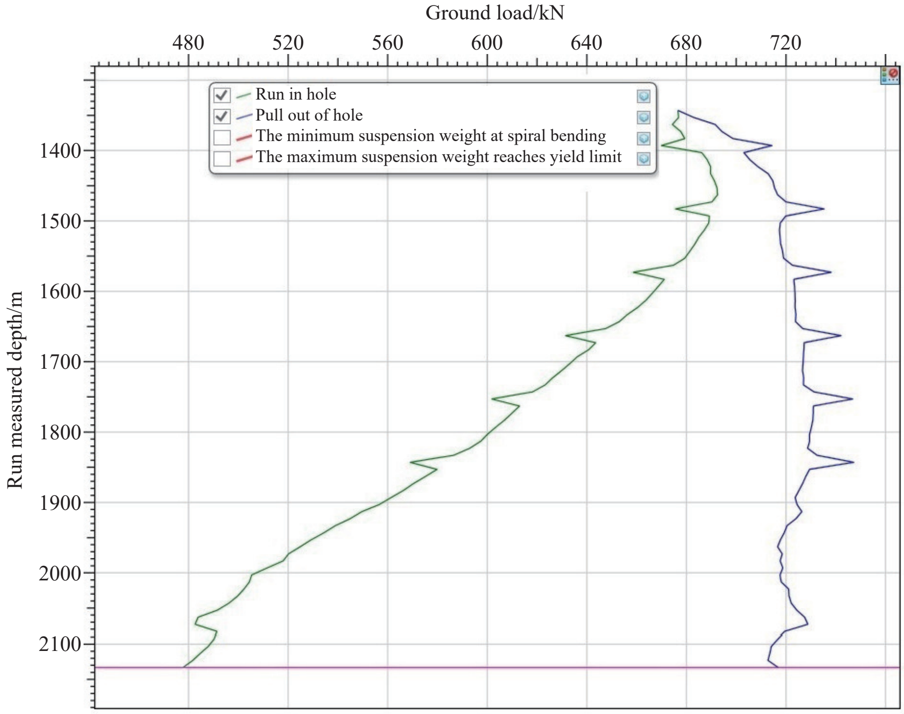

Fig. 13. Change of hook load of sand control string with depth when the friction coefficient being 0.4.

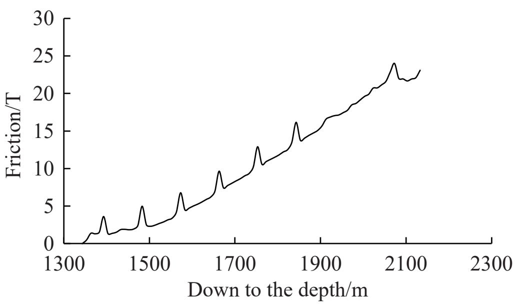

Fig. 14. Friction curve of sand control string with a friction coefficient of 0.4.

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