Large-scale experiments of the borehole instability on shale formation influenced by drill pipe rotation

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Abstract
Wellbore instability happens mostly in the shale formation. Early researches have studied thoroughly on the physicochemical and mechanical mechanism that causes instability. However, only a few works have considered the influence of field drilling operations, such as drill pipe rotation. In this paper, a true triaxial cell is used to simulate the downhole field situations, and a drill pipe rotation device is innovatively designed and implemented into the true triaxial cell. Using this facility, the influence of drill pipe rotation on shale instability has been performed. Different rotation speed, weight on bit, drilling fluid pressure, and microcracks on borehole have been considered. The enlargement of the wellbore is quantitatively plotted and compared. Results show that the drill pipe rotation contributes to a more enlargement of the wellbore, and a higher rotation speed causes a more severe collapse. The drill string weight on bit also contributes to the enlargement of the wellbore, with a larger weight on bit induces a larger diameter of the collapsed wellbore. Compared with the rotation speed and weight on bit, the influence of drilling fluid density is relatively less significant. However, the influence of microcracks caused by hitting of drilling tools is profound. For a cracked shale formation, the wellbore diameter can be enlarged for more than 40%. Then, the variation of borehole collapse with time and depth under drill pipe rotation influence is analyzed. In all of these four factors, the significant sequence is microcracks > weight on bit > rotation speed > drilling fluid pressure. In all the collapse phenomena, the collapse is more severe in the minimum horizontal stress direction. This is explained by the analysis of the stress distribution in the whole circumferential angle (360°) of the wellbore. Overall, this work fills the gap of the influence of drilling operations on wellbore instability.

Keywords
borehole enlargement, drill pipe rotation, true triaxial cell, wellbore instability
1 | INTRODUCTION

Drilling works are mostly carried out in sedimentary strata, 75% of which is composed of shale. Shales are fine-grained sedimentary rocks composed of clay, silt, and, in some cases, fine sand.¹ According to statistics, 90% of the borehole instability occurs in mud shale formation.²⁻⁴ The influence factors of shale borehole stability are very complex, which can be attributed to three aspects: physicochemical factors, mechanical factors, and engineering factors.⁵⁻⁶ At present, a lot of researches have performed relatively adequate research on physicochemical factors and mechanical factors.⁷⁻¹⁰

The effect of physicochemical factors is the reaction between shale and drilling fluid, including capillary action, permeation, hydrodynamic expansion and pressure diffusion between fluid and shale.²,¹¹ In the 1960s, researchers found that hydration between shale and drilling fluid was one of the important causes of borehole instability. Then, researches on physicochemical factors were carried out,¹² and a series of basic theories were set up, such as the hydration expansion pressure of shale,¹³ the concept of activity equilibrium,¹⁴ and Biot coupling theory.¹⁵ Then, more detailed researches on reducing the reaction between drilling fluid and shale to improve borehole stability were done, just like the magnitude of water activity and the properties of solutes,¹⁶,¹⁷ permeable membranes to describe the interaction,¹⁸ permeability pressure difference,¹⁹ shale membrane potential,²⁰,²¹ and so on. Recently, lots of researches on theoretical derivation²² and improving drilling fluid properties such as sealing,²³⁻²⁶ rheological property,²⁷⁻²⁹ and wettability³⁰,³¹ to slow down the drilling fluid invasion into brittle shale are carried out.

The mechanical factors mainly focused on the calculation of the distribution of borehole stress.³²⁻³³ The research method developed from linear elasticity to poroelasticity, from elastic analysis to plastic analysis, and from single field analysis to multi-field coupling analysis.³⁴⁻³⁷ The solving method developed from analytical, semi-analytical methods to numerical simulation methods including finite difference, finite element, boundary element, and discrete element, etc.³⁸⁻⁴³ Both isotropic and anisotropic of shale rock were considered. Based on the basic theories established a long time before,⁴⁴⁻⁴⁶ researches now focus on borehole stability under dynamic loading conditions,³⁶,²⁸ and the influence of anisotropic strata, including anisotropy of sedimentary tectonics,⁴⁷⁻⁵⁰ strength parameters,⁵¹ and elastic parameters.⁵²⁻⁵⁵ Using these contributions, more accurate predictions were achieved.

Compared with the physicochemical and mechanical factors, the study of engineering factors is very limited, due to the complex engineering activities and demanding of special facilities.⁵⁶,⁵⁷ The engineering factors include the drill pipe rotation, the friction, and collision of drill string vibration, the scouring effect of annular return velocity of drilling fluid, the swab/surge pressure. By establishing drill string vibration models and effective detection method under different working conditions, appropriate drilling tools could be determined and drill string vibration energy could be controlled to effectively reduce borehole enlargement.⁵⁸,⁵⁹ Some researches have been done on the scouring effect of drilling fluid, which shows that drilling fluid scouring effect depends on the drilling fluid pressure, return velocity, the thickness of mud cake, geological tectonic characteristics, formation rock damage, and so on. The larger the drilling fluid pressure, the greater the return velocity, the more obvious the scouring effect of drilling fluid on borehole stability.⁶⁰⁻⁶⁴

Because of the complexity of the disturbance mechanism of drill pipe rotation, there is no research on its influence on borehole instability. However, the drill pipe rotation has been considered in contributing to the severity of borehole instability. In Chinese Shengli Oilfield, the collapse of the shale formation is still very serious with appropriate mud weight and a special anti-collapse mud formulation. The weakening effect of shale immersed in the drilling fluid is also insignificant (Figure 1). Field drillers think one possible reason is the drill pipe rotation. Therefore, one innovative evaluation method should be proposed to quantitatively characterize the influence of the drill pipe rotation on borehole stability.

In this paper, a new facility is innovatively made by combining the drill pipe rotation device and a true triaxial cell. Then, experiments under the influence of drill pipe rotation are carried out on large-scale shale samples extracted from Shengli Oilfield. The tests are finished under different rotation speed, weight on bit, drilling fluid pressure, and for both intact and cracked shale rock. The borehole enlargement is quantitatively plotted and compared to analyze the severity of the wellbore collapse. This work can provide technical support for improving the stability of shale borehole during drilling operations.

![FIGURE 1](image_url)  The curve of compressive strength over time
EXPERIMENTS

2.1 Experimental facility

To study the influence of drill pipe rotation, two main parts should be available: (a) true triaxial cell to simulate the downhole situations and (b) drill pipe rotation device to simulate the drilling operations.

The true triaxial cell is mainly composed of two parts: (a) three-dimensional in situ stress applying part and (b) high-pressure drilling fluid injection part. The in situ stress applying part includes one high-pressure chamber, four pressurized cylinders, MTS servo-hydraulic power pump, a servo control system, the main control computer, and measuring systems. This part can apply triaxial stress to large-scale sample up to 100 MPa, and the push plate pressure cylinder is used here to push the sample out of the cavity after the test. The high-pressure drilling fluid injection part includes an MTS servo advection pump, an air compressor, drilling fluid conversion containers, a servo control system, the main control computer, and measuring systems. This enables us to inject high-pressure drilling fluid into the simulated borehole up to 80 MPa. The drilling fluid conversion container is an important part. The constant flux pump cannot be used to inject drilling fluid directly because the drilling fluid particles may block the pump. Therefore, the drilling fluid conversion vessel is divided into two parts by a piston, with the upper part contains water and the lower part contains drilling fluid. The constant flux pump can push the drilling fluid into the pressure cavity by injecting water into the conversion vessel and push the piston down. Figure 2 shows the schematic composition of the true triaxial cell and Figure 3 is the real picture. The full digital controller is used in the control system of the experimental equipment, which enables high control precision and high reliability. The parameters of drilling fluid pressure and displacement can be recorded and controlled in real time by the main control compute in the process of test.

The drill pipe rotation device is shown in Figure 4, which consists of a bearing plate, sealing rings, a waterproof motor, a motor fixing frame, and a simulated drill pipe. The bearing plate is used to place small parts and bear the external load. The sealing ring composed of inner and outer rings is used to seal high-pressure drilling fluid in the borehole and prevent drilling fluid from leaking off at the wellhead. The waterproof motor of different power is used to provide different rotation speed and prevent drilling fluid from invading. The motor fixing frame can guarantee the motor to work stably without shaking. The simulated drill pipe can simulate the drill pipe rotation with different rotation speed, weight on bit, and drilling fluid pressure.

In order to improve the effectiveness of test results, it is essential to set test conditions as close as possible to field conditions.

**FIGURE 2** Compositions of true triaxial cell. Note: $\sigma_v$ is overburden pressure, MPa; $\sigma_H$ is Maximum horizontal principal stress, MPa; $\sigma_h$ is Minimum horizontal principal stress, MPa; $\sigma_p$ is push pale pressure, MPa
to obtain experimental results approved by field engineers. And many scholars have adopted field parameters as experimental conditions in the hydraulic fracture experiments with triaxial pressure vessels. So the test focuses on the conditions in the design process, such as experimental material, test time, test load, geometric size, kinematic condition, and so on. In terms of experimental material, the real shale core is used in the middle of sample, and the field drilling fluid system is used in the experiment. In terms of test time, the time of simulation experiment is 15 days, generally similar to shale section soak time during field drilling. In terms of test load, the test applies in situ stress of 80-70-55 MPa, and the real drilling fluid pressure to the core. In terms of geometric size, the drilling operation parameters of Jiayu 1# during drilling shale section are used for reference. The drill bit size is 8 1/2 in. However, the borehole size is 1.05-1.1 larger due to the whirling of the drill bit. The pipe size is 5 in. So the ratio of pipe size to borehole size is about 50%-60%. In the experiment, the borehole size is selected as 30 mm, the drill pipe size is 16 mm, and the ratio is 53%. In terms of kinematic condition, the drilling rotation speeds are set as low rotation speed (0.136 g), medium rotation speed (0.242 g), and high rotation speed (0.242 g), according to the field drilling speed whose range is 0.042-0.284 g.

### 2.2 Sample preparation

The shale core is drilled from Shahejie formation of Shengli Oilfield with a depth of about 3500 m. As shown in Figure 5, the shale core is tight, brittle and has an obvious stratification development. The sample used in the true triaxial cell is a cube with a size of 300×300×300 mm. However, it is very difficult and expensive to get a shale sample with full size. The molding of shale into cement is a good choice. The water-lime-sand ratio is 0.45-1-1.8 here, which is adjusted to make its mechanical parameters similar to those of shale core. As shown in Figure 6, a cylinder hole with a diameter of 30 mm is drilled in the middle of the sample. Then, the shale rock with an artificial hole is pouring with the surrounding cement. The real picture of the artificial experimental sample is shown in Figure 7. To make it clearer for understanding, the schematic diagram of a sample is plotted in Figure 8. In the experiment, the sample is used to simulate the stratum, so the three principal stresses are applied to the sample (black part in Figure 8). The drill pipe rotation mainly occurs in the wellbore (blue part in Figure 8), and the device to realize the drill pipe rotation is the wellhead device, which is equipped with the waterproof motor and the motor fixing frame, as shown in Figure 4. Therefore, the external sample (black part in Figure 8) is fixed, but the internal drill pipe rotates in the wellbore (blue part in Figure 8).

### 2.3 Experimental procedures

The specific steps of the experiment are as follows:

1. Measure the size of length, width, and height of the experimental sample, take photographs and make records.
2. Place the sample onto the experimental platform and inject potassium polymer drilling fluid into the drilling fluid conversion container.
3. Push the sample into the experimental cavity and gradually apply triaxial stress to the rock sample up to the rated value. The triaxial stress is applied synchronously to ensure that the stress on the rock sample is uniform.

4. After the in situ stress meets the experiment requirements, keep the stress state unchanged. Inject drilling fluid through the advection pump to the desired pressure. The pressure conditions should be maintained for 15 days, and the waterproof motor is used to drive the drill pipe to rotate which can simulate the rotation state of the drill pipe.

5. On the 1st, 3rd, 5th, 7th, 9th, 11th, 13th, and 15th day, take down the sample and measure the borehole radius with a 3D laser scanning equipment and a fine and hard “L” shaped tool. The 3D laser scanning equipment can obtain the coordinates of points like (x.xxx, x.xxx, x.xxx) with a high accuracy of 0.001 mm, as shown in Figure 9, and the caliper measurement principle is shown in Figure 10.

6. After the measurement, continue the experiment following the steps above until the experiment is over.

7. After all the experimental procedures are completed, take down the sample, break it to take out the core, take photographs, and analyze.

2.4 | Experimental scheme

To achieve the experimental effect, a series of experimental schemes are carefully designed, as shown in Table 1.
3 | RESULTS

3.1 | No rotation of the drill pipe

The shale core images before and after the experiment are shown in Figures 11 and 12. When there is no drill pipe rotation, the borehole shape changes slightly and becomes a little oval (Figure 11). In the minimum horizontal principal stress direction, the damage is the most serious and the diameter increases by 4.83 mm with an enlargement ratio of 16.1%. While the borehole damage is small in the maximum horizontal principal stress direction (Figure 12), the borehole collapse is mainly caused by the effect of mechanics-chemistry coupling effect.

To quantitatively compare the borehole enlargement, 10 section faces along the borehole from top to bottom are selected evenly, as shown in Figure 13. The first section is the upper end of the core, which is 10 cm away from the upper surface of the sample, and the 10th section is the lower end of the core. Then, the section depth can be determined. The radii at the angle of 0°, 30°, 60°, 90°, 120°, 150°, 180°, 210°, 240°, 270°, 300°, and 330° are measured in all of the ten section faces. Then, the core caliper graph could be plotted using these 12 radii. Here, the zero degrees represent the maximum principal horizontal stress (Figure 14).

Using the method described above, the variance of borehole shape is presented in Table 2. With no drilling pipe rotation, borehole is under drilling fluid immersion state, and borehole stability is subjected to the mechanics-chemistry coupling effect. After the experiment of 15 days, a different degree of borehole collapse occurs at different depths and different orientations. However, borehole collapse near the minimum horizontal principal stress direction is the worst, whereas the borehole collapse near the maximum horizontal principal stress direction is very slight with tiny drops. By measurement and calculation, the borehole diameter enlargement ratio is 16.1%, just as shown in Table 2(5).

According to the measured data, the curve of borehole diameter enlargement ratio over time is shown in Figure 15. The curve of borehole collapse degree with the relative position of section is shown in Figure 16. In Figure 15, the borehole diameter enlargement ratio increases with time, which increases slowly on the 1st day and then increases rapidly. However, when time increases to the 5th day, the borehole diameter enlargement ratio increases slowly and remains basically unchanged. On the 5th day, the borehole diameter is 34.5 mm, and the ratio of it to the final borehole diameter is 87%, which is over 80%. Therefore, when there is no drill pipe rotation and the borehole is under the effect of mechanics-chemistry coupling, the collapse cycling time of the borehole is 5 days. In Figure 16, there is no obvious rule that the diameter enlargement ratio changes with depth, which may be caused by formation heterogeneity. But the borehole collapse is serious at the first section position which is the interface of different strata, and the drilling fluid invades more here. Whereas the borehole collapse is slight at the end section because of cuttings deposition.

3.2 | Influence of drilling speed

3.2.1 | Experimental results analysis

Experiments on drilling speed are carried out, compared with no rotation of drilling pipe. Rotation speeds of 0.060 g, 0.136 g, and 0.242 g are adopted here, which represent low rotation speed, medium rotation speed, and high rotation
speed, respectively. The shale core images before and after experiments are shown in Table 3. Table 3(a1)-(a3) shows the images before the experiment, Table 3(b1)-(b3) shows the images after the experiment, and Table 3(c1)-(g3) shows images of minimum and maximum horizontal principal stress direction after experiment.

Compared with the images before and after the experiment, the borehole shape after the experiment changes a lot, becoming elliptic with one end narrow and one end wide. In the three cases, the borehole collapses in different degree, with large or tiny drops. In the minimum horizontal principal stress direction, there are large drops (Table 3(c1)-(c3)). And there are tiny drops in the maximum horizontal principal stress orientation (Table 3(e1) and (e2)). Obviously, the collapse is more serious in the minimum horizontal principal stress orientation. As can be seen from Table 3, the rotation speed has an important influence on borehole damage. The bigger the rotation speed is, the greater the borehole shape changes. In the area with the most serious borehole damage, the diameter increases by 6.38 mm at a low rotation speed, which is 8.16 mm at a medium rotation speed, and 10.98 mm at high rotation speed.

### 3.2.2 Borehole shape analysis

Measure experimental data and map out 10 core caliper graph at low rotation speed, medium rotation speed, and high rotation speed, respectively, followed the method described above, as shown in Tables A1-A3, Appendix A. The most representative charts of the largest borehole diameter enlargement ratio are selected, respectively, as shown in Figure 17. Under rotation speed, the collapse of Figure 17 is more serious than that of Table 2 because of the fast drill pipe rotation speed.
By comparing the Figure 17A–C, it is found that the borehole diameter increases obviously under the disturbance of the drill pipe, especially near the direction of the minimum horizontal principal stress. However, there is a big difference in borehole diameter enlargement ratio at different drill pipe rotation. Obviously, borehole diameter enlargement ratio at high rotation speed is larger than that at medium speed and low speed. Under low rotation speed (Figure 17A), borehole diameter enlargement ratio is 21.3% after the experiment of 15 days, which increases by nearly 23% than that with no disturbance of drill pipe. Under medium rotation speed (Figure 17B), borehole diameter enlargement ratio is 27.2% after the experiment of 15 days, which increases by nearly 57% than that with no disturbance of drill pipe, 45% than that at low speed (0.060 g). Under high rotation speed (Figure 17C), the collapse is very serious because of the fast drill pipe rotation speed. The borehole diameter enlargement ratio is 36.6% after the experiment of 15 days, which increases by nearly 112% than that with no disturbance of drill pipe, 72% than that at low speed (0.060 g), and 37% than that at medium speed (0.136 g). It indicates that the drill pipe rotation has a huge impact on borehole stability which aggravates the borehole damage greatly. The greater the rotation speed, the more serious the borehole collapse. The main reason is that the borehole is under the influence of drill pipe disturbance, and the drill pipe rotation agitates the drilling fluid, which will increase its erosion of the borehole and result in a more complicated force on the borehole. The results are proved by the macroscopic observation images (Figure 18) and SEM image (Figure 19). A rough borehole face can be observed. The borehole collapse is more serious under drill pipe rotation.

Borehole collapse near the minimum horizontal principal stress direction is the most serious. However, borehole collapse near the maximum horizontal principal stress direction has large drops too under the drill pipe rotation.

3.2.3 | Borehole diameter analysis

According to the measured data, the curve of borehole diameter enlargement ratio over time is made as shown in Figure 20. The curve of borehole collapse degree with the relative position of the section is as shown in Figure 21. Compared with the three curves in Figure 20, it can be found that the growth rate of borehole diameter enlargement ratio increases with the rotation speed increases. But they have a consistent pattern of growth. The borehole diameter enlargement ratio increases with time, which increases rapidly in the first
5 days. When the time reaches the 5th day, the ratio of borehole diameter to final borehole diameter is 88.7% at a low rotation speed, 89.0% at a medium rotation speed, and 86.6% at high rotation speed which are all over 80%. The borehole collapse mainly occurred in the first 5 days. After that, the borehole diameter enlargement ratio increases slowly and remains basically unchanged. Therefore, when the drill pipe rotation speed is 0.060 g, 0.136 g, and 0.242 g, the borehole collapse cycling time is 5 days when the borehole is under the mechanics-chemistry coupling effect. In Figure 21, the larger the rotation speed is, the more severe the average borehole collapse degree is. When the drill pipe rotates purely, the position where borehole collapses more severely is uncertain because of formation heterogeneity. But the borehole collapse in the downhole is small because deposition and accumulation of cuttings at the downhole weaken the influence of drill pipe disturbance.

### 3.3 Influence of weight on bit

#### 3.3.1 Experimental results analysis

Here, the weight on bit is simulated by flexible deformation of drill pipe (Figure 4), and an approximate sinusoidal buckling of the drill pipe is referred. The small flexible deformation of drill pipe means a low weight on bit and the large flexible deformation of drill pipe means a high weight on bit.

Under the low and high weight on bit, the shale core images before and after the experiment are shown in Table 4. In Table 4(b1) and (b2), the borehole shape changes greatly and becomes an eccentric oval. Where the borehole damage is the most serious, the diameter increases by 9.12 mm under the low weight on bit, and 11.48 mm under the high weight on bit. Compared with Table 4(c1)-(f2), there are significant differences.
large drops in all orientations when the drill pipe rotates at 0.136 \( g \) under weight on bit. However, there are more serious damage in the minimum horizontal stress orientation and relatively slight damage in the maximum horizontal stress orientation. Obviously, borehole collapse is more serious under high weight on bit.

### 3.3.2 Borehole shape analysis

Measure experimental data and map out 10 core caliper graph under low weight on bit and high weight on bit, respectively, followed the method described above, as shown in Tables A4 and A5, Appendix A. The most representative charts of largest borehole diameter enlargement ratio are selected, respectively, as shown in Figure 22. Potassium polymer drilling fluid system is used, and the rotation speed of the drill pipe is 0.136 \( g \).

From Figure 22, we can find borehole collapses severely under the low weight on bit and high weight on bit. Compared with Figure 22A,B, borehole collapses more severely under high weight on bit. Under low weight on bit, borehole diameter enlargement ratio is 30.4% after the experiment of 15 days, which increases by nearly 12\% than that of pure drill pipe rotation. Under high weight on bit, borehole diameter enlargement ratio is 38.3\% after the experiment of 15 days, which increases by nearly 41\% than that of pure drill pipe rotation, 26\% than that of low weight on bit. It indicates that the weight on bit has a big impact on borehole stability. The
main reason is that the increase of weight on bit causes the increase of drill pipe deformation, which causes drilling fluid more severe agitation and erosion. Meanwhile, the collision of drill pipe to the borehole is also intensified. The larger the weight on bit, the more serious the borehole collapse because of the combined action of drilling fluid erosion and drill pipe collision to the borehole. The results are proved by the macroscopic observation images (Figure 23) and SEM image (Figure 24). In these figures, both smooth borehole face (Figures 23A and 24A) and rough borehole face (Figures 23B and 24B) show in the sample with small drill pipe deformation. The rough borehole face means the drill pipe rotation plays an important role in the borehole collapse. And the smooth borehole face means the wear of the drill pipe deformation works. However, Figure 24A shows that the borehole face is not so smooth, which means the wear of the drill pipe deformation is not the only factor and the drill pipe rotation also plays a role in borehole stability. Under the weight on bit, borehole collapse near the minimum horizontal principal stress direction is the most serious. However, there are large drops near the maximum horizontal principal stress direction too. The borehole collapse is more serious in the deformation part of the drill pipe.

3.3.3 Borehole diameter analysis

According to the measured data, the curves of borehole diameter enlargement ratio over time under low and high weight on bit respectively are made as shown in Figure 25. The curve of borehole collapse degree with the relative position of the section is as shown in Figure 26. In Figure 25, the borehole
diameter enlargement ratio increases with time under low weight on bit, and it increases quickly in the 1st day, slowly in 2-3 day, quickly 4-5 day again, but basically remains unchanged after 5 days. Under high weight on bit, the borehole diameter enlargement ratio increases with time, which increases slowly on the 1st day and then increases rapidly. However, when the time increases to the 5th day, the borehole diameter enlargement ratio increases slowly and remains basically unchanged. When the time reaches the 5th day, the ratio of borehole diameter to final borehole diameter is 88.6% under low weight on bit, which is 93.2% under high weight on bit. Therefore, no matter the weight on bit is low or high, the borehole collapse cycling time is 5 days. In Figure 26, there are one obvious crest under low weight on bit and two crests under high weight on bit on the curve. The crest means the borehole collapses severely, whose position on the borehole corresponds to the flexible deformation position of drill pipe exactly. The influence of drill pipe deformation under weight on bit on borehole stability is more obvious in the place where the drill pipe deformation is large, and it is greatly weakened in the place far away from the drill pipe deformation.

3.4 | Influence of drilling fluid pressure

3.4.1 | No microcrack core

Experimental results analysis
Here, the microcrack means the crack caused by drilling engineering, like the bit hitting the core. Figure 27 shows the borehole with no microcrack after coring. For the no microcrack core, the shale core images before and after the experiment are shown in Table 5. As can be seen from Table 5(b1) and (b2), the borehole shape changes very greatly and becomes an eccentric oval, with one end round and the other pointed. From Table 5(c1)-(d2), we can see that borehole collapses very unevenly, severely somewhere, however very slightly somewhere. Probably it is due to the heterogeneity of the shale. Compared with the images from Table 5(c1)-(f2), we can find that there are large drops in the minimum principal stress direction, and the borehole collapses slightly in the maximum principal stress direction. Where the borehole damage is the most serious, the borehole diameter increases by 9.36 mm when lower density drilling fluid is used and increases by 8.52 mm when higher density drilling fluid is used.

Borehole shape analysis
Measure experimental data and map out 10 core caliper graph under lower density and higher density drilling fluid with no microcrack on borehole, respectively, followed the method described above, as shown in Tables A6 and A7, Appendix A. The most representative charts of largest borehole diameter enlargement ratio are selected, respectively, as shown in Figure 28. In the experiments, the potassium polymer drilling...
 fluid system is used, and the rotation speed of the drill pipe is 90 rpm.

From Figure 28A, we can get that when lower density drilling fluid (0.9 g/cm³) is used, the borehole damage is relatively serious. The borehole is under the mechanics-chemistry coupling effect, and borehole diameter enlargement ratio is 31.2% after the experiment of 15 days, which increases by only 15% than that of drilling fluid system above. From Figure 28B, we can get that when higher density drilling fluid (1.1 g/cm³) is used, the borehole damage is relatively serious. The borehole is under the mechanics-chemistry coupling effect, and borehole diameter enlargement ratio of higher density is 28.4% after the experiment of 15 days, which increases by only 5% than that of drilling fluid system above. The borehole diameter enlargement ratio increases small which indicates that the drilling fluid pressure has a relatively smaller impact on borehole stability than the drill pipe rotation. Most likely the shale formation of Jiyang depression is tight enough, and the weakening effect of drilling fluid invasion on borehole rock strength is greatly weakened. Under the influence of drilling fluid density, borehole collapse near the minimum horizontal principal stress direction is the worst. However, there are small drops near the maximum horizontal principal stress orientation.

Borehole diameter analysis
According to the measured data, the curve of borehole diameter enlargement ratio over time is made as shown in Figure 29. The curve of borehole collapse degree with the relative position of the section is as shown in Figure 30. Compared with two curves, the curves change in a different way at the beginning, however, and in a similar way later when drilling fluid systems of different density are used. When low density drilling fluid is used, the borehole diameter enlargement ratio increases with time and increases slowly in the first 3 days, then increase rapidly. But when the time is up to 5 days later, the borehole diameter enlargement ratio remains unchanged. At the 5th day, the ratio of the borehole to the final borehole diameter is 82%. When high density drilling fluid is used, the borehole diameter enlargement ratio increases rapidly at the beginning. But when the time is up to 5 days later, the borehole diameter enlargement ratio remains unchanged. At the 5th day, the ratio of borehole diameter to the final borehole diameter is 91%. So, when different density drilling fluid is used, the borehole is under mechanics-chemistry coupling effect and borehole collapse cycling time is 5 days. In Figure 30, when there is no microcrack
on the borehole, the average borehole collapse degree under low drilling fluid pressure is more serious than that under high drilling pressure. At the beginning position, the borehole collapse is more serious because of the interface, and at the end position, the borehole collapse is relatively slight because of the cuttings deposition.

3.4.2 Microcrack core

Experimental results analysis
The microcrack is mainly caused by the hitting of drilling tools on the borehole, which will have a big impact on the borehole stability, as shown in Figure 31.

The core images before and after the experiment are shown in Table 6. As can be seen from Table 6(b1) and (b2), when there is microcrack, the borehole shape changes greatly and becomes elliptic greatly both under the low and high density.

In Table 6(c1)-(f2), we can see that borehole collapses severely both in the minimum direction and in the maximum direction. However, the borehole collapse in the minimum direction is more serious. Where the borehole damage is the most serious, the diameter increases by 13.95 mm when low density drilling fluid is used and increases by 12.63 mm when the high density drilling fluid is used, which are bigger than the diameter caused by other factors. It indicates that microcrack on borehole has a very important impact on borehole stability.
TABLE 5  Core images before and after the experiment

| Lower density | Higher density |
|---------------|---------------|
| ![A1] | ![A2] |
| ![B1] | ![B2] |
| ![C1] | ![C2] |
| ![D1] | ![D2] |
| ![E1] | ![E2] |
| ![F1] | ![F2] |
Borehole shape analysis

Measure experimental data and map out 10 core caliper graph under lower density and higher density drilling fluid with microcrack, respectively, followed the method described above, as shown in Tables A8 and A9, Appendix A. The most representative charts of largest borehole diameter enlargement ratio are selected, respectively, as shown in Figure 32. Potassium polymer drilling fluid system is used, and the rotation speed of drill pipe is 90 rpm.

When the lower density drilling fluid (0.9 g/cm³) is used, the borehole damage is very serious (Figure 32A). The borehole diameter enlargement ratio is 46.5% after the experiment of 15 days, which increases by nearly 49% than that of no microcrack on the borehole. When the higher density drilling fluid (1.1 g/cm³) is used, then the borehole damage is very serious (Figure 32B). The borehole is under the mechanics-chemistry coupling effect, and borehole diameter enlargement ratio is 45.1% after the experiment of 15 days, which declines by only 3.1% than that of lower density drilling fluid, but increases 33% than that of no microcrack. It indicates that microcrack has a huge impact on borehole stability, but drilling fluid density’s impact is relatively smaller. When there exists microcrack, the borehole strength is reduced, and the drilling fluid is easier to invade the borehole which will further exacerbate the borehole strength. So borehole collapses severely. Borehole collapse near the minimum horizontal principal stress direction is the most serious. However, there are large drops near the maximum horizontal principal stress direction too.

Borehole diameter analysis

According to the measured data, the curve of borehole diameter enlargement ratio over time with microcrack on the borehole is made as shown in Figure 33. The curve of borehole collapse degree with the relative position of the section is as shown in Figure 34. In Figure 33, borehole diameter enlargement ratio increases with time and increases rapidly at the beginning, especially in the 1st day. Maybe it is caused by the microcrack failure. When the time increases to the 5th day, the borehole collapse degree increases very slowly, basically remains unchanged. Under lower density drilling fluid, the borehole diameter is 43.5 mm on the 5th day, and the ratio of it to the final borehole diameter is 93%. Under higher density drilling fluid, the borehole diameter is 40.5 mm, and the ratio is 96%. So, the borehole collapse...
TABLE 6  Core images before and after the experiment

| Lower density          | Higher density          |
|------------------------|-------------------------|
| ![Image A1]            | ![Image A2]             |
| ![Image B1]            | ![Image B2]             |
| ![Image C1]            | ![Image C2]             |
| ![Image D1]            | ![Image D2]             |
| ![Image E1]            | ![Image E2]             |
| ![Image F1]            | ![Image F2]             |
mainly happens in the first 5 days. Therefore, when there exists microcrack on the borehole, the borehole is subjected to mechanics-chemistry coupling and the borehole collapse cycling time is 5 days. In Figure 34, when there is microcrack on the borehole, the average borehole collapse degree under low drilling fluid pressure is more serious than that under high drilling fluid pressure. In the shale section, there is no obvious rule on borehole collapse degree and depth. However, the borehole collapse is the worst where there is microcrack on the borehole.

3.5 Discussion part

The content above shows large-scale physical simulating experiment results under drill pipe disturbance, and a preliminary analysis of the drill pipe rotation speed, weight on bit, drilling fluid pressure, and borehole microcracks on the influence of borehole stability. Because of the complexity of the borehole instability mechanism under the drill pipe disturbance, it is difficult to propose corresponding theoretical models. However, the experimental results can still be analyzed according to the corresponding wellbore stability theory. The specific rock mechanical parameters of Shahejie formation in Jiyang depression are shown in Table 7.

Figure 35 presents the wellbore stress distribution including radial stress and tangential stress. The maximum horizontal stress is in the north-south direction, and the minimum horizontal stress is in the east-west direction. The degrees 0, 30, ..., 330 represent the circumferential angle of the wellbore. The yellow dotted circles with radii of 1, 1.5, 2, 2.5, and 3 represent dimensionless distance $\xi$. In the color bar, the unit of the number is MPa. At the maximum horizontal stress direction (90°), radial stress increases with the radial distance, while tangential stress also increases with radial distance. Both radial stress and tangential stress are influenced by the circumferential angle because of the nonuniform hydrostatic stress.

Using the stress calculated in Figure 35, the wellbore collapse density is calculated in Figure 36. It shows that at the minimum horizontal stress direction (1°), the collapse density is much higher than the maximum horizontal stress direction (91°). It explains the reason that wellbore collapse is always more severe in the minimum horizontal stress direction. At the minimum horizontal stress direction, the collapse density is 1.438 g/cm³. The test performed used the drilling fluid of 1.3 g/cm³. Therefore, it guarantees that wellbore collapse happens in the minimum horizontal stress direction. Meanwhile, due to the bedding plane effect, there is a sharp change in some degrees (46°, 136°, 226°, 316°).

4 CONCLUSIONS

Through carrying out large-scale experiments of borehole stability test under drill pipe rotation, the influence of drill pipe rotation speed, weight on bit, drilling fluid pressure, and microcrack on the borehole is explored systematically, and the following main conclusions are obtained.

1. The drill pipe rotation speed has a great influence on borehole stability. The greater the rotation speed, the greater the borehole collapse. The main reason is that...
the drill pipe rotation agitates the drilling fluid, which will increase its erosion of the borehole and result in a more complicated force on the borehole. When the drill pipe rotation speed is 120 rpm, the borehole diameter enlargement ratio is 36.6%, increasing by 112% than that of no drill pipe disturbance, 72% than that of the low speed (60 rpm), and 37% than that of the medium speed (90 rpm). This indicates that when conditions permit, low rotation speed should be adopted in the section of the shale. However, at a different rotation speed, the borehole collapse in the downhole is small because deposition and accumulation of cuttings at the downhole weaken the influence of drill pipe disturbance. The borehole collapse occurs seriously in the direction of the minimum horizontal principal stress.

2. The weight on bit also has a great influence on the stability of the borehole. The higher the weight on bit, the more serious the borehole collapse because of the combined action of drilling fluid erosion and drill pipe collision to the borehole. When the weight on bit is higher, the borehole diameter enlargement ratio is 38.3%, increasing by 41% than that of pure drill pipe rotation, and 26% than that of low weight on bit. Where borehole collapses most severely the flexible deformation position of drill pipe exactly. The influence of drill pipe deformation under weight on bit on borehole stability is more obvious in the place where the drill pipe deformation is large, and it is greatly weakened in the place far away from the drill pipe deformation. The borehole collapse mainly occurs in the minimum horizontal principal stress direction, but there are also big drops in the maximum horizontal principal stress direction. Through comparative analysis, it is concluded that the influence of weight on bit on borehole stability is greater than that of rotation speed.

3. The drilling fluid pressure has a small influence on the stability of borehole. When using drilling fluid of 0.9 g/cm³, the borehole diameter enlargement ratio is 31.2%, increasing by 15% than that of drilling fluid of 1.3 g/cm³, 10% than that of drilling fluid of 1.1 g/cm³. When microcrack exists on the borehole, the borehole damage is very serious and the borehole diameter enlargement ratio of both drilling fluid system (0.9 g/cm³ and 1.1 g/cm³) exceeds 40%. The borehole collapse is the worst where there is microcrack on the borehole, which means the microcrack has a huge impact on borehole stability. In this case, the borehole collapse is severe both in the direction of the minimum horizontal principal stress and the maximum horizontal principal stress, but it is more serious in the direction of the minimum horizontal principal stress.

**FIGURE 35** Radial stress and tangential stress distribution at the bottom hole

**FIGURE 36** Wellbore collapse mud density around the wellbore

| Poisson’s ratio \(v\) | Overburden pressure \(\sigma_u\) (MPa) | Maximum horizontal principal stress \(\sigma_H\) (MPa) | Minimum horizontal principal stress \(\sigma_h\) (MPa) | Pore pressure equivalent density \(\rho_d\) (g/cm³) | Cohesion \(S\) (MPa) | Internal angle \(\varphi\) (°) | Weak plane cohesion \(S\) (MPa) | Weak plane internal angle \(\varphi\) (°) | Biot’s coefficient \(\alpha\) |
|----------------------|------------------|------------------|------------------|--------------------------|----------------|-------------------|-------------------|-------------------|------------------|
| 0.189                | 80               | 70               | 55               | 1.45                     | 19.1           | 21.9              | 12                | 15                | 0.965            |

**TABLE 7** Parameters of rock mechanical parameters used for calculation
4. By comparing the influence degree of various factors on borehole stability under the drill pipe rotation, it can be seen that the sequence of influence factors is microcrack on borehole > weight on bit > rotation speed > drilling fluid density. Under the action of different factors, the borehole collapse cycling time is basically stable, about 5 days. There is not an obvious variation of borehole collapse degree and depth (relative position of the section). But the borehole collapse is severe on the top because of the interface and drilling fluid’s invasion, and relatively slight on the downhole because of the cuttings deposition.

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CONFLICT OF INTEREST

None declared.

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REFERENCES

1. Petrowiki; 2015. https://petrowiki.org/Borehole_instability
2. Lal M. Shale stability: drilling fluid interaction and shale strength. In: SPE Asia Pacific Oil and Gas Conference and Exhibition. Society of Petroleum Engineers; 1999.
3. Meng M, Silvio B, Miska S. Wellbore stability in naturally fractured formations featuring dual-porosity/single-permeability and finite radial fluid discharge. J Petrol Sci Eng. 2019;174:790–803.
4. Montilva JC, Van Oort E, Brahim R, et al. Using a low-salinity high-performance water-based drilling fluid for improved drilling performance in Lake Maracaibo. In: SPE Annual Technical Conference and Exhibition. Society of Petroleum Engineers; 2007.
5. Xiaohua Z, Liu W. The effects of drill string impacts on wellbore stability. J Petrol Sci Eng. 2013;109:217–229.
6. Meng M, Miska S. Dynamic wellbore stability analysis under tripping operations. Rock Mech Rock Eng. 2019;44(6):1–21.
7. Zhao X, Qiu Z, Sun B, Liu S, Xing X, Wang M. Formation damage mechanisms associated with drilling and completion fluids for deepwater reservoirs. J Petrol Sci Eng. 2019;173:112–121.
8. Zhao X, Qiu Z, Zhao C, Xu J, Zhang Y. Inhibitory effect of water-based drilling fluid on methane hydrate dissociation. Chem Eng Sci. 2019;199:113–122.
9. Liu K, Gao D, Wang Y, Yang Y. Effect of local loads on shale gas well integrity during hydraulic fracturing process. J Nat Gas Sci Eng. 2017;37:291–302.
10. Liu K, Gao D, Taleghani AD. Analysis on integrity of cement sheath in the vertical section of wells during hydraulic fracturing. J Petrol Sci Eng. 2018;168:370–379.
11. Van Oort E. On the physical and chemical stability of shales. J Petrol Sci Eng. 2003;38(3–4):213–245.
12. Van Oort E. A novel technique for the investigation of drilling fluid induced borehole instability in shales. In: Rock Mechanics in Petroleum Engineering. Society of Petroleum Engineers; 1994.
13. Chenevert ME. Adsorptive pore pressures of argillaceous rocks. In: The 11th US Symposium on Rock Mechanics (USRMS). American Rock Mechanics Association; 1969.
14. Yew CH, Chenevert ME, Wang CL, Osisanya S. Wellbore stress distribution produced by moisture adsorption. SPE Dril Eng. 1990;5(04):311–316.
15. Sherwood JD. Biot poroelasticity of a chemically active shale. Proc R Soc Lond A. 1909;1993(440):365–377.
16. Yu M, Chenevert ME, Sharma MM. Chemical–mechanical wellbore instability model for shales: accounting for solute diffusion. J Petrol Sci Eng. 2003;38(3–4):131–143.
17. Ghassemi A, Diek A. Linear chemo-poroelasticity for swelling shales: theory and application. J Petrol Sci Eng. 2003;38(3–4):199–212.
18. Schlemmer R, Friedheim JE, Growcock FB, Bloys JB, Headley JA, Polnaszek SC. Chemical osmosis, shale, and drilling fluids. SPE Drill Completion. 2003;18(04):318–331.
19. Nguyen V, Abousleiman Y, Hoang S. Analysis of wellbore instability in drilling through chemically active fractured-rock formations. SPE J. 2007;14(2):286–301.
20. Al-Bazali TM, Zhang J, Chenevert ME, et al. A rapid, rigsite deployable, electrochemical test for evaluating the membrane potential of shales. In: SPE Annual Technical Conference and Exhibition. Society of Petroleum Engineers; 2007.
21. Al-Bazali T, Zhang J, Chenevert ME, Sharma MM. Factors controlling the compressive strength and acoustic properties of shales when interacting with water-based fluids. Int J Rock Mech Min Sci. 2008;45(5):729–738.
22. Chen G, Ewy RT, Yu M. Analytic solutions with ionic flow for a pressure transmission test on shale. J Petrol Sci Eng. 2010;72(1–2):158–165.
23. Akhtarmanesh S, Shaharabi M, Atashnezhad A. Improvement of wellbore stability in shale using nanoparticles. J Petrol Sci Eng. 2013;112:290–295.
24. Chao Z, Jie C, Shugang L, et al. Experimental study comparing the microscopic properties of a new borehole sealing material with ordinary cement grout. Environ Earth Sci. 2019;78(5):149.
25. Abbas AK, Fiori RE, Ahmed A, Alsaba M. Laboratory analysis to assess shale stability for the Zubair Formation, Southern Iraq. J Nat Gas Sci Eng. 2018;56:315–323.
26. Dong B, Meng M, Qiu Z, Lu Z, Ye Z, Zhong H. Formation damage prevention using microemulsion in tight sandstone gas reservoir. J Petrol Sci Eng. 2019;173:101–111.
27. Zhao K, Sun H, Dou L, et al. Physicochemical characteristics of hard brittle shale and associated wellbore instability. In: Proceedings of the International Field Exploration and Development Conference 2017. Singapore: Springer; 2019:661–672.
28. Pourkhalil H, Nakhaei A. Effect of nano ZnO on wellbore stability in shale: an experimental investigation. J Petrol Sci Eng. 2019;173:880–888.
29. Meng M, Qiu ZS. Experiment study of mechanical properties and microstructures of bituminous coals influenced by supercritical carbon dioxide. *Fuel*. 2018;219:223-238.

30. Yue Y, Chen S, Wang Z, et al. Improving wellbore stability of shale by adjusting its wettability. *J Petrol Sci Eng*. 2018;161:692-702.

31. Yang X, Shang Z, Shi Y, et al. Influence of salt solutions on the permeability, membrane efficiency and wettability of the Lower Silurian Longmaxi shale in Xiushan, Southwest China. *Appl Clay Sci*. 2018;158:83-93.

32. Chen G, Chenevert ME, Sharma MM, Yu M. A study of wellbore stability in shales including poroelastic, chemical, and thermal effects. *J Petrol Sci Eng*. 2003;38(3-4):167-176.

33. Zeynali ME. Mechanical and physico-chemical aspects of wellbore stability during drilling operations. *J Petrol Sci Eng*. 2012;82:120-124.

34. Roshan H, Rahman SS. Analysis of pore pressure and stress distribution around a wellbore drilled in chemically active elastoplastic formations. *Rock Mech Rock Eng*. 2011;44(5):541-552.

35. Ekbote S, Abousleiman Y. Porochemical solution for an inclined borehole in a transversely isotropic formation. *J Eng Mech*. 2002;128(7):754-763.

36. Meng M, Zamanipour Z, Miska S, Yu M, Ozbayoglu EM. Dynamic stress distribution around the wellbore influenced by surge/swab pressure. *J Petrol Sci Eng*. 2019;172:1077-1091.

37. Li X, Jaffal H, Feng Y, El Mohtar C, Gray KE. Wellbore breakouts: Mohr-Coulomb plastic rock deformation, fluid seepage, and time-dependent mudcake buildup. *J Nat Gas Sci Eng*. 2018;52:515-528.

38. Kang Y, Yu M, Miska SZ, Takach N. Wellbore stability: a critical review and introduction to DEM. In: *SPE Annual Technical Conference and Exhibition*. Society of Petroleum Engineers; 2009.

39. Gaede O, Karpfinger F, Jocker J, Prioul R. Comparison between analytical and 3D finite element solutions for borehole stresses in anisotropic elastic rock. *Int J Rock Mech Min Sci*. 2012;51:53-63.

40. Zhu H, Zhu J, Rutter R, Zhang J, Zhang HQ. Sand erosion model prediction, selection and comparison for electrical submersible pump (ESP) using CFD method. In: *ASME 2018 5th Joint US-European Fluids Engineering Division Summer Meeting*. American Society of Mechanical Engineers; 2018;V003T17A003.

41. Zhang H, Yin S, Aadnoy BS. Finite-element model of borehole breakouts for in situ stress determination. *Int J Geomech*. 2018;18(12):04018174.

42. Zhang H, Yin S, Aadnoy BS. Poroelastic modeling of borehole breakouts for in-situ stress determination by finite element method. *J Petrol Sci Eng*. 2018;162:671-684.

43. Li X, Feng Y, El Mohtar CS, Gray KE. Transient modeling of borehole breakouts: a coupled thermo-hydro-mechanical approach. *J Petrol Sci Eng*. 2019;172:1014-1024.

44. Fairhurst C, Cook N. The phenomenon of rock splitting parallel to a free surface under compressive stress. In: *Proceedings of the First Congress of the International Society of Rock Mechanics*, Lisbon, Portugal; 1966:1:687-692.

45. Bradley WB. Failure of inclined boreholes. *J Energy Res Technol*. 1979;101(4):232-239.

46. Li X, El Mohtar CS, Gray KE. Modeling progressive breakouts in deviated wellbores. *J Petrol Sci Eng*. 2019;175:905-918.

47. Al-Bazali TM, Zhang J, Chenevert ME, et al. An Experimental Investigation on the Impact of Capillary Pressure, Diffusion Osmosis, and Chemical Osmosis on the Stability and Reservoir Hydrocarbon Capacity of Shales. Offshore Europe: Society of Petroleum Engineers; 2009.

48. Shamsuzzoha M. Analysis of borehole failure related to bedding plane. 2011.

49. Lee H, Ong SH, Azeeemuddin M, Goodman H. A wellbore stability model for formations with anisotropic rock strengths. *J Petrol Sci Eng*. 2012;96:109-119.

50. Zhu H, Zhu J, Zhang J, Zhang HQ. Efficiency and critical velocity analysis of gravitational separator through CFD simulation. In: *ASME 2017 International Mechanical Engineering Congress and Exposition*. American Society of Mechanical Engineers; 2017;V007T09A067.

51. Weijermars R. Mapping stress trajectories and width of the stress-perturbation zone near a cylindrical wellbore. *Int J Rock Mech Min Sci*. 2013;64:148-159.

52. Tran MH, Abousleiman YN. Anisotropic porochemoelectroelastic solution for an inclined wellbore drilled in shale. *J Appl Mech*. 2013;80(2):020912.

53. Zhang J. Borehole stability analysis accounting for anisotropies in drilling to weak bed planes. *Int J Rock Mech Min Sci*. 2013;55:155-170.

54. Gao J, Deng J, Lan K, Feng Y, Zhang W, Wang H. Porothermoelastic effect on wellbore stability in transversely isotropic medium subjected to local thermal non-equilibrium. *Int J Rock Mech Min Sci*. 2017;96:66-84.

55. Gao J, Deng J, Lan K, Song Z, Feng Y, Chang L. A porothermoelastic solution for the inclined borehole in a transversely isotropic medium subjected to thermal osmosis and thermal filtration effects. *Geothermics*. 2017;67:114-134.

56. Field DJ, Swarbrick AJ, Haduch GA. Techniques for successful application of dynamic analysis in the prevention of field-induced vibration damage in MWD tools. In: *SPE/IADC Drilling Conference*. Society of Petroleum Engineers; 1993.

57. Dykstra MW, Chen D, Warren TM, Azar JJ. Drillstring component mass imbalance: a major source of downhole vibrations. *SPE Drill Completion*. 1996;11(04):234-241.

58. Santos H, Placidio J, Wolter C. Consequences and relevance of drillstring vibration on wellbore stability. In: *SPE/IADC Drilling Conference*. Society of Petroleum Engineers; 1999.

59. Ghasemloonia A, Rideout DG, Butt SD. A review of drillstring vibration modeling and suppression methods. *J Petrol Sci Eng*. 2015;131:150-164.

60. Burns FL, Andrews A, Lingle R. Cement-plug leakage and drilling damage evaluated. *Oil Gas J (United States)*. 1982;80(47):424-438.

61. Fuenkajorn K, Daemen J. Drilling-induced fractures in borehole walls. *J Petrol Technol*. 1992;44(02):210-216.

62. Dai C, Zhao F. Drilling Fluid Chemistry. *Oilfield Chemistry*. Singapore: Springer; 2018:21-84.

63. Bao A, Hazlett RD, Babu DK. A discrete, arbitrarily oriented 3D plane-source analytical solution to the diffusivity equation for modeling reservoir fluid flow. *SPE J*. 2017;22(05):1609-1623.

64. Bao A, Gildin E. Data-Driven Model Reduction Based on Sparsity-Promoting Methods for Multiphase Flow in Porous Media. *Geothermics*. 2018;69:1-15.

65. Shah J, Chen M, Jin Y, Zhang GQ. Analysis of fracture propagation behavior and fracture geometry using a tri-axial fracturing system in naturally fractured reservoirs. *Int J Rock Mech Min Sci*. 2017;96:1143-1152.

66. Cui Y, Liu D, Yao Y, Li J, Qiu Y. Geological controls on prediction of coalbed methane of No. 3 coal seam in Southern Qinshui Basin, North China. *Int J Coal Geol*. 2011;88(2-3):101-112.
67. Lehtonen A, Cosgrove JW, Hudson JA, Johansson E. An examination of in situ rock stress estimation using the Kaiser effect. Eng Geol. 2012;124:24–37.
68. Fallahzadeh SH, Rasouli V, Sarmadivaleh M. An investigation of hydraulic fracturing initiation and near-wellbore propagation from perforated boreholes in tight formations. Rock Mech Rock Eng. 2015;48(2):573–584.
69. Ma X, Zhou T, Zou Y. Experimental and numerical study of hydraulic fracture geometry in shale formations with complex geologic conditions. J Struct Geol. 2017;98:53–66.
70. Ma X, Zou Y, Li N, Chen M, Zhang Y, Liu Z. Experimental study on the mechanism of hydraulic fracture growth in a glutenite reservoir. J Struct Geol. 2017;97:37–47.
71. Guo T, Rui Z, Qu Z, Qi N. Experimental study of directional propagation of hydraulic fracture guided by multi-radial slim holes. J Petrol Sci Eng. 2018;166:592–601.
72. Liu X, Nair SD, Cowan M, et al. A novel method to evaluate cement-shale bond strength. In: SPE International Symposium on Oilfield Chemistry. Society of Petroleum Engineers; 2015.
73. Liu J, Yao Y, Liu D, et al. Experimental simulation of the hydraulic fracture propagation in an anthracite coal reservoir in the southern Qinshui basin, China. J Petrol Sci Eng. 2018;168:400–408.
74. Gong W. Bending of rotating drill string. Oil Field Mach. 1986;6:21–29.
75. Sun B, Fu W, Wang Z, et al. Characterizing the rheology of methane hydrate slurry in a horizontal water-continuous system. SPE J. 2019;2(3):102–118.

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**APPENDIX A**

**TABLE A1** Core borehole diameter enlargement curve chart (low rotation speed)

| 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|
| ![Diagram 1](image1.png) | ![Diagram 2](image2.png) | ![Diagram 3](image3.png) | ![Diagram 4](image4.png) | ![Diagram 5](image5.png) |
| ![Diagram 6](image6.png) | ![Diagram 7](image7.png) | ![Diagram 8](image8.png) | ![Diagram 9](image9.png) | ![Diagram 10](image10.png) |
### TABLE A2  Core borehole diameter enlargement curve chart (medium rotation speed)

|   |   |   |   |   |   |
|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 |   |
|   |   |   |   |   |   |
| 6 | 7 | 8 | 9 | 10 |   |

### TABLE A3  Core borehole diameter enlargement curve chart (high rotation speed)

|   |   |   |   |   |   |
|---|---|---|---|---|---|
| 1 | 2 | 3 | 4 | 5 |   |
|   |   |   |   |   |   |
| 6 | 7 | 8 | 9 | 10 |   |
**TABLE A4**  Core borehole diameter enlargement curve chart (low weight on bit)

|   |   |   |   |   |
|---|---|---|---|---|
| ![Chart 1](image1) | ![Chart 2](image2) | ![Chart 3](image3) | ![Chart 4](image4) | ![Chart 5](image5) |
| ![Chart 6](image6) | ![Chart 7](image7) | ![Chart 8](image8) | ![Chart 9](image9) | ![Chart 10](image10) |

**TABLE A5**  Core borehole diameter enlargement curve chart (high weight on bit)

|   |   |   |   |   |
|---|---|---|---|---|
| ![Chart 1](image11) | ![Chart 2](image12) | ![Chart 3](image13) | ![Chart 4](image14) | ![Chart 5](image15) |
| ![Chart 6](image16) | ![Chart 7](image17) | ![Chart 8](image18) | ![Chart 9](image19) | ![Chart 10](image20) |
| TABLE A6 | Core borehole diameter enlargement curve chart (low density with no microcrack) |
|----------|--------------------------------------------------------------------------------|
| 1        | ![Diagram](image1) | 2 | ![Diagram](image2) | 3 | ![Diagram](image3) | 4 | ![Diagram](image4) | 5 | ![Diagram](image5) |
| 6        | ![Diagram](image6) | 7 | ![Diagram](image7) | 8 | ![Diagram](image8) | 9 | ![Diagram](image9) | 10 | ![Diagram](image10) |

| TABLE A7 | Core borehole diameter enlargement curve chart (high density with no microcrack) |
|----------|--------------------------------------------------------------------------------|
| 1        | ![Diagram](image11) | 2 | ![Diagram](image12) | 3 | ![Diagram](image13) | 4 | ![Diagram](image14) | 5 | ![Diagram](image15) |
| 6        | ![Diagram](image16) | 7 | ![Diagram](image17) | 8 | ![Diagram](image18) | 9 | ![Diagram](image19) | 10 | ![Diagram](image20) |
**TABLE A8**  Core borehole diameter enlargement curve chart (low density with microcrack)

| 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|
| ![Diagram 1](image1.png) | ![Diagram 2](image2.png) | ![Diagram 3](image3.png) | ![Diagram 4](image4.png) | ![Diagram 5](image5.png) |
| 6 | 7 | 8 | 9 | 10 |

**TABLE A9**  Core borehole diameter enlargement curve chart (high density with microcrack)

| 1 | 2 | 3 | 4 | 5 |
|---|---|---|---|---|
| ![Diagram 1](image1.png) | ![Diagram 2](image2.png) | ![Diagram 3](image3.png) | ![Diagram 4](image4.png) | ![Diagram 5](image5.png) |
| 6 | 7 | 8 | 9 | 10 |