Numerical analysis on fracture initiation from radial micro-hole in anisotropy formation

Yumei Li1 | Tao Zhang1,2 | Yiming Zheng3 | Jinhua Zhang4 | Tao Wen5 | Shibin Sun6

1Beijing Key Laboratory of High Dynamic Navigation Technology, Beijing Information Science & Technology University, Beijing, China
2High Dynamic Automation Technology Hejian Co., Ltd, Hejian, China
3Beijing Union University, Beijing, China
4CNPC Bohai Drilling Engineering Co., Ltd, Tianjin, China
5CNPC Tarim Oilfield Branch, Korla, China
6Offshore Oil Engineering Co. Ltd., CNOOC, Tianjin, China

Correspondence
Yumei Li, Beijing Key Laboratory of High Dynamic Navigation Technology, Beijing Information Science & Technology University, Beijing 100101, China. Email: liyumei3680238@163.com

Funding information
The authors gratefully acknowledge the financial support of the National Natural Science Foundation of China, Grant/Award Number: 41871348 and 41802197; Beijing Municipal Education Commission “Science and Technology General Project”, Grant/ Award Number: KM202111232004; Key Research Cultivation Program of Beijing Information Science & Technology University, Grant/ Award Number:2121YJPY220 and 2020KYH224; The Strategic Cooperation Technology Projects of CNPC and CUPB Grant/Award Number: ZLZX2020-03; PhD Research Funding Project of Liaoning Province, China, Grant/Award Number: 2020-BS-289

Abstract
The radial jet drilling (RJD) technology is typically developed to open multiple lateral micro-holes from a main wellbore to the formation. The multiple groups of 3D numerical models of radial micro-holes through a main well are built by incorporating the pore hydro-mechanical coupling effects. A number of sensitivity analyses were conducted on the effects of the radial jetting azimuth, the stress anisotropy, and the elastic anisotropy on the rock fracture initiation of the micro-holes. As revealed from the results, the fracture initiation from the micro-hole exhibited the diversified characteristics with the increase in the jetting azimuth. Thus, the jetting azimuth of the nozzle was recommended to be designed in the interval of 0°-30°. A higher elastic modulus anisotropy ratio $K$ and a lower Poisson’s ratio anisotropy ratio $K’$ caused the significant rigidity characteristics of the rock, which increased the possibility of fracture initiation in the horizontal direction; a lower elastic modulus anisotropy ratio $K$ and a higher Poisson’s ratio anisotropy ratio $K’$ caused the strong rigidity characteristics, so the rock could not easily fracture in the vertical direction. Several suggestions were given that the rock is easy to be broken by selecting a smaller jetting azimuth angle and a more significant in-situ stress difference. The numerical simulation results agree well with field experiment results, with an average accuracy of 97.17%. The proposed numerical model has a good performance in predicting the fracture initiation pressure of the radial micro-hole in anisotropy formation.

KEYWORDS
elastic anisotropy, radial jet drilling, radial jetting azimuth, rock failure, stress anisotropy
The radial jet drilling (RJD) technology has been increasingly applied for stimulating low-performing wells, and simultaneously open up oil and gas channels in the rock formation. This application attempts to perforate multiple lateral micro-holes from a main wellbore along the radial directions, which can facilitate the petroleum production. RJD technology is capable of creating a considerable jetting energy to break the rock with a high-pressure water impacting effect on the target rock. On that basis, the lateral micro-holes with a radius of 20-50 mm and a length of 10-100 m can be formed. Thus, this technology can create hydraulic multi-fractures to enhance the fracture complexity and reservoir productivity with a low cost.

The benefit from the RJD technology has been extensively investigated at home and abroad, and radial horizontal wells and the hydraulic fracturing joint operation for stimulating low-performing geothermal wells, the low-permeability formation, and the hard formation have been proposed to be possible to achieve. The radial drilling fracturing has been innovatively proposed by integrating radial drilling and hydraulic fracturing. According to Figure 1, the radial micro-holes are generated from the main vertical wellbore through the hydro-jet drilling, and the hydraulic fractures are subsequently operated with fractures initiating from these fracture directions. Compared with conventional technologies for the hydraulic fracturing stimulation, the fracture initiation points and the pressure prediction of lateral micro-holes from a main wellbore have aroused considerable attention in the development of complex fracture networks. Over the past few years, some researches and field applications (eg, the self-propulsion force of the hydraulic jet bit, the radial horizontal extension limit, the borehole trajectory measurement, the rock breaking capacity of the jet bit, the calculation of hydraulic parameters) have been conducted. Obviously, the prediction of the fracture initiation in radial lateral boreholes should be studied in depth to more effectively control the variability of fractures.

A growing number of existing studies have been conducted on the hydraulic fracture initiation as guided by perforated holes instead of radial micro-holes. Indeed, numerous basic researches can be learnt from. The fracture initiating rules and the FIP prediction in the radial jet drilling (RJD) as guided by radial micro-holes are critical to the fracturing design. Liu Qingling et al developed an analytical model to calculate the fracture initiation pressure (FIP), the initial fracture location in radial lateral boreholes, as well as to conduct the sensitivity analysis (eg, the in-situ stress, orientation, length, and diameter of radial micro-holes). Tiankui Guo et al built a 3D model of fracture propagation as guided by multi-radial holes, and they conducted a range of sensitivity analysis (eg, geometric parameters of radial slim holes, the rock Young’s modulus, Poisson’s ratio, the stress difference, and the reservoir permeability) on the hydraulic fracture propagation. As impacted by the essential difference between perforation holes and radial micro-holes, the stress fields vary between radial micro-hole wells and perforated wells. Specific to the studies on fracture initiation points and expansion directions, fractures initiating from radial holes were numerically and experimentally investigated. As indicated from the results, fracture initiation directions showed a relationship with the direction of the maximum horizontal stress. For the study on the FIP prediction of radial micro-holes, Gong investigated the factors of the radial azimuth, length, and diameter of multi-radial holes on the fracture initiation pressure.

In the present study, the multiple groups of 3D finite-element numerical models of micro-holes through the radial horizontal well were built by incorporating the pore hydro-mechanical coupling effects based on the ABAQUS. A number of investigations were conducted on the effects of the radial jetting azimuth, the elastic anisotropy, and the in-situ stress anisotropy on the fracture initiation point and FIP of the micro-holes by conducting the sensitivity analysis. This study on the multi-fracture simulation could lay a theoretical basis for improving the fracture complexity in reservoirs with the poorly developed natural fracture, as well as for optimizing the parameters design of radial jet drilling (RJD).
2 | THEORETICAL METHODOLOGY

2.1 | Transverse isotropy formation

Horizontal bedding planes generally exist in layered rock formations. Layered formations can be considered the transverse isotropy medium with physical properties that are symmetric about an axis that is normal to a plane of isotropy. The symmetry global coordinates system XYZ and the local coordination system X’Y’Z’ are defined. The schematic diagram of the transverse isotropic formations with global coordination system is shown in Figure 2. The transversely isotropic formations are symmetrical about the Y axis. The horizontal plane is XOZ, the vertical plane is ZOY and XOY. The Young’s modulus perpendicular to the isotropic plane is \( E_x \) and parallel to the isotropic plane is \( E_z \). The Poisson’s ratio perpendicular to the isotropic plane is \( \nu_y \) and parallel to the isotropic plane is \( \nu_x \).

Given the linear elastic behavior exhibited by the materials, the relations of strains and stresses with nine independent parameters are defined as\(^{24-26} \):

\[
\begin{bmatrix}
\varepsilon_{xx} \\
\varepsilon_{yy} \\
\varepsilon_{zz} \\
\varepsilon_{xy} \\
\varepsilon_{xz} \\
\varepsilon_{yz}
\end{bmatrix} = \begin{bmatrix}
1/E_x - \nu_{xy}/E_y & -\nu_{xz}/E_z & 0 & 0 & 0 \\
-\nu_{yx}/E_y & 1/E_y - \nu_{yz}/E_z & 0 & 0 & 0 \\
0 & 0 & 1/G_{yz} & 0 & 0 \\
0 & 0 & 1/G_{xz} & 1/E_x & 0 \\
0 & 0 & 1/G_{xy} & 0 & 1/E_y
\end{bmatrix} \begin{bmatrix}
\sigma_{xx} \\
\sigma_{yy} \\
\sigma_{zz} \\
\sigma_{xy} \\
\sigma_{xz} \\
\sigma_{yz}
\end{bmatrix}
\]

(1)

where \( \varepsilon_{ij} \) denotes the linear strain; \( \sigma_{ij} \) is stress tensors. Young’s modulus \( E \), shear modulus \( G \), and Poisson’s ratio \( \nu \) are related to the principal directions.

The transverse isotropy formations will have two scenarios. The constitutive equation of plane stress is expressed as:

\[
\begin{bmatrix}
\varepsilon_{x'} \\
\varepsilon_{y'} \\
\gamma_{x'y'}
\end{bmatrix} = \begin{bmatrix}
1/E_x & -\nu_{xy}/E_y & 0 \\
1/E_y & 0 & 0 \\
1/G_{xy} & 0 & 0
\end{bmatrix} \begin{bmatrix}
\sigma_{x'} \\
\sigma_{y'} \\
\gamma_{x'y'}
\end{bmatrix}
\]

(2)

Moreover, the constitutive equation of the plane strain in the local coordinate system is written as:

\[
\begin{bmatrix}
\varepsilon_{x'} \\
\varepsilon_{y'} \\
\gamma_{x'y'}
\end{bmatrix} = \begin{bmatrix}
1/E_x - \nu_{xy}/E_y & -\nu_{xz}/E_z & 0 \\
1/E_y - \nu_{yz}/E_z & 0 & 0 \\
1/G_{xy} & 0 & 0
\end{bmatrix} \begin{bmatrix}
\sigma_{x'} \\
\sigma_{y'} \\
\gamma_{x'y'}
\end{bmatrix}
\]

(3)

With the assumption of \( S' \) as the compliance matrix in Equations (2) and (3), the compliance matrix via the coordinate transformation is written as:

\[
S = T_{\sigma}^T S' T_{\sigma}
\]

(4)

\[
T_{\sigma} = \begin{bmatrix}
\cos^2 \beta & \sin \beta \cos \beta & 2\sin \beta \cos \beta \\
\sin^2 \beta & \cos^2 \beta & -2\sin \beta \cos \beta \\
-\sin \beta \cos \beta & \sin \beta \cos \beta & \cos^2 \beta - \sin^2 \beta
\end{bmatrix}
\]

(5)

where \( T_{\sigma} \) denotes the transformation matrix of stress; \( \beta \) represents the material angle.

2.2 | Stresses at radial micro-hole wall

In this part, a global coordinate system was established. The vertical well is drilled along the vertical stress \( \sigma_y \). The X axis was aligned with the maximum horizontal stress \( \sigma_{H} \), while the Y axis was aligned with the minimum horizontal stress \( \sigma_h \). The schematic of radial lateral and stresses of an arbitrary point \( M \) at radial micro-hole wall is illustrated in Figure 3. Accordingly, the in-situ stress tensor is expressed as:

\[
\begin{bmatrix}
\sigma_{xx} & 0 & 0 \\
0 & \sigma_{yy} & 0 \\
0 & 0 & \sigma_{zz}
\end{bmatrix} = \begin{bmatrix}
\sigma_{H} & 0 & 0 \\
0 & \sigma_{h} & 0 \\
0 & 0 & \sigma_{v}
\end{bmatrix}
\]

(6)
The stresses at the radial borehole wall due to the changing pore pressure are expressed below:

\[
\begin{align*}
\sigma_r &= P_w - \sigma_{p} \left( P_w - P_p \right) \\
\sigma_\theta &= -P_w + \left( \sigma_{p} + \sigma_z \right) - 2 \left( \sigma_{p} - \sigma_z \right) \cos(2\phi) \\
\sigma_z &= -P_w + \left( \sigma_{p} + \sigma_r \right) - 2 \left( \sigma_{p} - \sigma_r \right) \cos(2\phi) \\
\sigma_{rw} &= 2 \sigma_{r} \sin\phi \\
\sigma_{w} &= \sigma_{w} = 0
\end{align*}
\]

where \( \sigma_r, \sigma_\theta, \) and \( \sigma_z \) are the normal stress in the \( r, \theta, \) and \( z \) direction, respectively, MPa; \( \sigma_{p} \) represents the pore pressure; \( \sigma_{p} \) is the fluid pressure, MPa. Stresses at radial micro-hole wall due to the changing pore pressure are expressed below:
where \( \sigma_1 \) is perpendicular to the plane, while the orientations of \( \sigma_2 \) and \( \sigma_3 \) in relative to the radial borehole axis line are defined as:

\[
\gamma = \frac{1}{2} \tan^{-1} \left( \frac{2\sigma_{up}}{\sigma_u - \sigma_v} \right)
\] (12)

3 | MODEL DEVELOPMENT

Some assumptions are proposed: (a) the thermal effect will not be considered in the whole simulation; (b) fracturing fluid is incompressible in the static state steady; (c) the rock is considered poroelastic, transversely isotropic medium; (d) the rock formation is horizontal or nearly horizontal in ideal conditions; (e) gravity is not considered.

3.1 | Geometry and meshing

In the present study, multiple groups of geometry model of formation-jet orifice via the radial horizontal well are built for the simulation. The angle between the jetting direction of the nozzle and the maximum horizontal principal stress (\( \sigma_H \)) direction is the jetting azimuth \( \phi \). The geometry is a "semi-circle" 3D model (Figure 4). The outer diameter of the model was 4000 mm, the inner diameter of the wellbore is 139.7 mm, and the inner diameter of the micro-hole is \( \Phi = 20.0 \) mm.

Specific to the model, the orifice of the micro-hole was orthogonal to the wellbore. To increase the grid accuracy at the intersection of the micro-hole and the wellbore, a layered cutting method should be used to refine the grid (Figure 5). The displacement pore pressure coupling hexahedral element C3D8P is adopted in the fracture initiation modeling of the radial horizontal well. After the meshing, the elements and nodes of micro-holes and main wellbore are defined. The meshing models with the jetting azimuth (0°-90°) are illustrated in Figure 6(A)-(F).

3.2 | Description of method

The mechanical parameters of hard rocks for the sensitivity analysis are listed in Table 1. The Young’s modulus \( E_{vert} \) and Poisson’s ratio \( \nu_{vert} \) perpendicular to the isotropic plane are constant, while the Young’s modulus \( E_{hor} \) and Poisson’s ratio \( \nu_{hor} \) paralleling to the isotropic plane are changing. The tensile strength was 2.0 MPa. Moreover, the saturation, the fluid permeability, the porosity, the fluid density, and the formation pore pressure are set.\(^ {15} \)

Considering the pore hydro-mechanical coupling effects, the geometrical model of wellbore and the micro-holes, and the simulation analysis process are set as follows. Before the geostatic analysis, the rock elements and rock nodes are pre-selected and defined. The displacement constraints are imposed on the surface of model. First, geostatic equilibrium analysis is conducted. Through the “predefined fields” part, the three-dimensional ground stresses (\( \sigma_V = 30 \) MPa, \( \sigma_H = 26 \) MPa, and \( \sigma_h = 20 \) MPa) are applied to the predefined rock elements to simulate the in situ stress equilibrium. And, the pore pressure of 16 MPa is applied to the predefined rock nodes. Subsequently, the birth and death processing method in the transient analysis of FEM is used to kill and remove the elements of the main wellbore and micro-holes after the equilibrium of the ground stress, which could simulate the main wellbore drilling and the micro-holes opening. Lastly, the transient analysis is conducted to simulate the dynamic consolidation process. The surface load of the fracturing fluid is applied onto the inner wall of the wellbore and the micro-hole step by step. An average change of the pressure build-up 16 MPa-60 MPa is set. Meanwhile, the pore pressure is applied.

FIGURE 4 Geometry model of micro-hole

FIGURE 5 Cutting model
to the element nodes. The dynamic calculation amplitude of 10 steps is imposed to compute the fracture initiation point and FIP of the micro-holes. The fracture is initiated when the maximum principal stress around the micro-holes wall reaches the tensile strength of rock with the increase in the surface load on the internal surface. Figure 7 illustrates the schematic diagram of the boundary conditions of the model.

4 | RESULTS AND DISCUSSION

4.1 | Jetting azimuth

An investigation is conducted on the effects of the jetting azimuth of the micro-hole on the fracture initiation point

TABLE 1 Model parameters of hard rocks for the sensitivity analysis

| Items                  | Value   | Unit |
|------------------------|---------|------|
| $E_{vert} = E_y$       | 30.61   | MPa  |
| $E_{hor} = E_x = E_z$  | 39.4-44.34 | MPa |
| $\nu_{vert} = \nu_y$   | 0.223   |      |
| $\nu_{hor} = \nu_x = \nu_z$ | 0.242-0.287 |      |
| Tensile strength       | 2       | MPa  |
| Friction angle         | 19      | deg. |
| Porosity               | 0.03    |      |
| Saturation             | 1       |      |
| Pore pressure          | 16      | MPa  |
| Permeability           | 0.0001  | md   |

FIGURE 6 The FEM meshing model at different jetting azimuth angles of 0°-90°

FIGURE 7 FEM analytical methods under the boundary conditions
in the anisotropy reservoirs (Figure 8). The inner surface load of the wellbore and the jetting pressure of the jet nozzle acts directly on the inner wall of the wellbore and micro-hole, and the jetting azimuth ranged from 0° to 90°. By complying with the tensile failure criterion, the rock failure happens when the maximum principal stress exceeds the tensile strength of the rock.

As indicated from the result, the rock started to fracture from the upper and lower ends of the root of the micro-hole at the jetting azimuth of 0°, and the fracture tended to propagate along the $\sigma_V$ direction. Next, the maximum principal stress is relatively larger, and it could be easy to break. At the jetting azimuth of 15°-30°, the maximum principal stress concentration point begins to incline to the horizontal maximum stress $\sigma_H$. The fracture initiation point tends to disperse and expand along the $\sigma_V$. At the jetting azimuth of 45°-60°, the maximum principal stress is concentrated on the upper and lower ends of the root of the micro-nozzle. At the jetting azimuth of 90°, the maximum tensile stress point approached to the borehole wall which is the first point of destruction on the borehole wall. As indicated from the comprehensive analysis, the fracture initiation from the micro-hole exhibits the diversified characteristics with the increase in the jetting azimuth of the micro-hole. As impacted by the ultra-high pressure jetting, the rock medium is destroyed primarily in the form of stress wave. Subsequently, the diameter of the micro-nozzle is enlarged by the quasi-static pressure. Furthermore, the fracture initiation point is largely concentrated at the maximum principal stress. Thus, the jetting azimuth of the nozzle should be designed in the interval of 0°-30°.

### 4.2 Elastic anisotropy

That the anisotropy ratio of Young’s modulus of the bedding formation is defined as $K = \frac{E_{\text{hor}}}{E_{\text{vert}}}$, and that of

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**Figure 8** Simulation results of the fracture initiation position at different jetting azimuth angles of 0°-90°
Poisson’s ratio of the bedding formation is defined as $K' = \nu_{\text{hor}} / \nu_{\text{vert}}$. As one result of the simulation, the fracture initiation pressure simulation results versus $K$ and $K'$ at different jetting azimuth angles of $0^\circ$, $30^\circ$, $60^\circ$, and $90^\circ$ in the Radial jet drilling (RJD) are illustrated in Figure 9, respectively.

In the region of a higher elastic modulus anisotropy ratio $K$ and a lower Poisson’s ratio anisotropy ratio $K'$, the rock exhibits the strong rigidity characteristics in the horizontal direction, so it could be more likely to be fractured. In the region of a lower elastic modulus anisotropy ratio $K$ and a higher Poisson’s ratio anisotropy ratio $K'$, the rock exhibits the strong rigidity characteristics in the vertical direction, while the higher initiation pressure causes the rock to be difficult to fracture.

Under the identical ground stress conditions, a range of sensitivity analysis on the effects of $K$ and $K'$ on the FIP was conducted. Figure 10 shows the fracture initiation pressure (FIP) versus jetting azimuth curves for the representative values of Young’s modulus anisotropy $K = 0.8$, 1, 1.2, 1.5, respectively. As revealed from the results, with the jetting azimuth angle of $0^\circ$ as an example, under the Poisson’s ratio anisotropy of $K' = 1.5$, the elastic modulus anisotropy $K$ is altered from 0.8 to 1.5, and the fracture
initiation pressure decreased by 10.8 MPa. Figure 11 presents the FIP versus Poisson’s ratio anisotropy $K'$ curves for representative values of the jetting azimuth of 0°, 30°, 60°, and 90°.

4.3 | Stress anisotropy

To demonstrate the effects of the in-situ stress non-dimensional anisotropy ratio $\sigma_H/\sigma_H$ on the FIP of the micro-hole in radial jet drilling (RJD), several numerical studies are conducted for the normal fault condition of $\sigma_V > \sigma_H > \sigma_H$. Under the constant vertical in-situ stress $\sigma_V$, the horizontal in-situ stress ratio $\sigma_H/\sigma_H = 0.5$, 0.7, 1, respectively. The multiple sets of the calculation models are developed to conduct the sensitivity studies on in-situ stress ratios ($\sigma_H/\sigma_H$) on the jet breaking effect of the jet nozzle. Figure 12 presents the simulation results of the maximum principal stress versus the jetting azimuth for representative values of $\sigma_H/\sigma_H$.

According to the results, the maximum principal stress is greater at the smaller ground stress ratio $\sigma_H/\sigma_H$ under the identical jetting azimuth angle and distance. The slope of the maximum principal stress curve is larger when the jetting azimuth angle $\phi < 30^\circ$, which demonstrates that the maximum principal stress exhibited more sensitivity to the differences of the ground stress. The maximum principal stress curve exhibits a relatively gentle slope when the jetting azimuth angle $\phi$ is in the interval of $30^\circ$-$90^\circ$. According to the comprehensive analysis, some suggestions are proposed that the rock could be easily broken by selecting smaller jetting azimuth angles and larger in-situ stress differences, which could effectively improve the efficiency of rock breaking in the drilling process.

5 | CASE ANALYSIS

In order to prove the practicability of the 3D numerical model of FIP prediction of radial micro- holes, the field application experiment is conducted in well Nan XX-14, China. The field application apparatus combination schematic of the radial jet drilling (RJD) simulation experiment system is shown in Figure 13.

The vertical depth of radial horizontal well is 2540 m, and the inner diameter of the wellbore is 139.7 mm. The diameter of the jet nozzle is 25.0 mm, the number of the forward orifices is 3, the number of the backward orifices is 5, and the jetting azimuth is 90°. The roughness of wellbore wall is 1 mm, and the friction coefficient is 0.3. The jetting fluid is clean water, the density is 988 kg/m³, and the viscosity is 0.549 mPa·s. The treating pressure is 25-71 MPa, and the slurry proppant concentration is 35-115 kg/m³. The anisotropy ratio of Young’s modulus $K = 0.8$, and anisotropy ratio of Poisson’s ratio $K’ = 1.2$.

The fracturing construction curve of the well Nan XX-14 is shown in Figure 14.

In the field experiment, it can be seen that fracture initiation pressure is 68.2 MPa from hydraulic fracturing construction curve. Figure 15 shows the comparison of numerical simulation results (Fn) and experiment results (Fe) of the fracture initiation pressure, respectively. It is obvious that the numerical simulation results Fn agrees well with field experiment results Fe, with an average
accuracy of 97.17%. Therefore, the proposed numerical model has a good performance in predicting the fracture initiation pressure of the radial micro-hole in anisotropy formation.

6 | CONCLUSION

In the present study, multiple groups of 3D numerical models of micro-holes through a main wellbore are established by incorporating the pore hydro-mechanical coupling effects based on the ABAQUS. The effects of the jetting azimuth, the elastic anisotropy, and the in-situ stress anisotropy on the FIP and initiation point of the micro-holes are investigated by conducting the sensitivity analysis. The conclusions can be drawn as follows:

1. The fracture initiation from the micro-hole showed the diversified characteristics with the increase in the jetting azimuth of the nozzle. The fracture initiation
2. The study revealed that the rock exhibited the strong rigidity characteristics in the horizontal direction in the region of higher elastic modulus anisotropy ratio $K$ and lower Poisson’s ratio anisotropy ratio $K'$, thereby increasing the possibility of fracture initiation. Besides, in the region of lower elastic modulus anisotropy ratio $K$ and higher Poisson’s ratio anisotropy ratio $K'$, the rock exhibits the strong rigidity characteristics in the vertical direction, and the higher initiation pressure causes the rock to be difficult fracture.

3. The maximum principal stress is greater at the ground stress ratio $\sigma_h/\sigma_H$ smaller under the identical jetting azimuth angle and distance. The slope of the curve is larger when the jetting azimuth angle $\varphi < 30^\circ$, which demonstrated that the maximum principal stress is more sensitive to the differences of the ground stress. The slope of the curve is relatively gentle when the jetting azimuth angle is in the interval of $30^\circ$-$90^\circ$. Some suggestions are proposed that the rock could be easily broken by selecting smaller jetting azimuth angles and larger in-situ stress differences, so the efficiency of rock breaking in the drilling process could be effectively improved.

4. The field application experiment is conducted for FIP prediction of the radial jet drilling (RJD). The numerical simulation results agree well with field experiment results, with an average accuracy of 97.17% of well Nan XX-14, China. The proposed numerical model has a good performance in predicting the fracture initiation pressure of the radial micro-hole in anisotropy formation.

ACKNOWLEDGMENTS
The authors gratefully acknowledge the financial support of the National Natural Science Foundation of China, Grant/Award Number: 41871348 and 41802197; Beijing Municipal Education Commission “Science and Technology General Project”, Grant/Award Number: KM202111232004; Key Research Cultivation Program of Beijing Information Science & Technology University, Grant/Award Number: 2121JYPY220 and 2020KYNH224; The Strategic Cooperation Technology Projects of CNPC and CUPB Grant/Award Number: ZLZX2020-03; PhD Research Funding Project of Liaoning Province, China, Grant/Award Number: 2020-BS-289.

CONFLICT OF INTEREST
None declared.

ORCID
Yumei Li https://orcid.org/0000-0001-5555-157X

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**How to cite this article:** Li Y, Zhang T, Zheng Y, Zhang J, Wen T, Sun S. Numerical analysis on fracture initiation from radial micro-hole in anisotropy formation. *Energy Sci Eng*. 2021;9:2449-2460. https://doi.org/10.1002/ese3.999