Influence of heterogeneity, natural fracture, and bedding plane on fracture propagation in the vicinity of a borehole

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Abstract: The majority of lost circulation events during drilling include drilling fluid losses through natural or drilling-induced fractures, but this problem can be prevented by understanding fracture propagation behavior. However, studies have mostly focused on the influence of natural fracture and bedding planes on hydraulic fracture propagation, and few studies have explored the fracture propagation in the vicinity of a borehole. Therefore, the present paper intends to simulate the fracture propagation in the vicinity of a borehole under the joint impact of heterogeneity, natural fracture, bedding planes, and borehole. The theoretical model of flow-rock failure process analysis [20] was introduced, and the uniaxial compressive testing results of Longmaxi shale were obtained to verify the present model. Then, fracture propagation models in the vicinity of a borehole were proposed by considering heterogeneity, bedding planes, and natural fracture. Numerical findings were analyzed and discussed. Results indicated that heterogeneity, bedding planes, and natural fracture significantly influenced fracture propagation in the vicinity of the borehole. As such, this influence should be considered in the analysis and treatment of lost circulation. This study could help elucidate how lost circulation could be prevented during drilling in fractured formations.

1. Introduction
Lost circulation is one of the trickiest problems encountered during drilling [1]. In lost circulation, drilling fluid is partially or completely lost into formations during drilling [2]. Lost circulation leads not only to drilling fluid loss and formation damage but also to the induced wellbore instability, blowouts, and pipe sticking; consequently, lost circulation causes huge economic losses and long non-production time (NPT) [2-12]. The majority of lost circulation events during drilling include drilling fluid losses through natural or drilling-induced fractures; thus, knowledge about fluid loss-related fracture propagation behavior can help prevent this problem [2-3], especially fracture propagation in the vicinity of a borehole.

To understand the fracture propagation in the vicinity of a borehole for lost circulation, Salehi [13] proposed a fracture growth model by using a cohesive zone model (CZM) implemented in FEM software. Kostov et al. [14] also developed a similar fracture propagation model for lost circulation by using the CZM. Feng and Gray [15-16] designed a lost circulation model by using the CZM and Abaqus software. They found that dynamic mud circulation is involved in this lost circulation model. However, studies have mostly focused on drilling-induced fractures for static and dynamic mud circulation, and few studies have explored the influence of natural fracture and bedding planes on fracture propagation in the vicinity of a borehole. Numerous studies have been conducted on the
influence of natural fracture and bedding planes on hydraulic fracture propagation [17-34]. In general, analytical, numerical, and physical models have been utilized; among them, numerical models are the most useful for the analysis of fracture propagation [17-34]. However, these models have mostly described the influence of natural fracture and bedding planes on hydraulic fracture propagation. Few models have been established for the fracture propagation in the vicinity of a borehole under the joint impact of natural fracture, bedding planes, and borehole.

In this study, the flow-rock failure process analysis (F-RFPA) code was utilized to simulate the fracture propagation in the vicinity of a borehole, enhance the understanding on how it could be influenced by natural fracture and bedding planes, and elucidate the measures on how to prevent lost circulation during drilling.

2. Numerical modeling
The F-RFPA code (Dalian Mechanics Software Co., Ltd., China) was utilized to simulate the fracture propagation in the vicinity of a borehole. In the following part, the theoretical model was introduced [35-37].

2.1. Governing equations
The following equations are used:
(1) Equilibrium equation
\[
\frac{\partial \sigma_{ij}}{\partial x_j} + X_j = 0 \quad (i, j = 1, 2, 3)
\] (1)
where \(\sigma_{ij}\) is the total stress in the \(ij\)-plane, and \(X_j\) is the body force in the \(j\)th direction.

(2) Strain–displacement relation
\[
\varepsilon_{ij} = \frac{1}{2}(u_{i,j} + u_{j,i})
\] (2)
where \(\varepsilon_{ij}\) is the strain in the \(ij\)-plane, and \(u_i\) is the displacement in the \(i\)th direction.

(3) Constitutive equation
\[
\sigma'_{ij} = \sigma_{ij} - \alpha P_p \delta_{ij} = \lambda \delta_{ij} \varepsilon_v + 2G \varepsilon_{ij}
\] (3)
where \(\varepsilon_v\) is given as
\[
\varepsilon_v = \varepsilon_{11} + \varepsilon_{22} + \varepsilon_{33}
\] (4)
where \(\sigma'_{ij}\) is the effective stress in the \(ij\)-plane, \(P_p\) is the pore pressure, \(\alpha\) is the coefficient of pore-fluid pressure, \(\lambda\) is the Lame’s coefficient, \(G\) is the shear modulus, \(\delta_{ij}\) is the Kronecker constant, \(\varepsilon_v\) is volume strain, and \(\varepsilon_{11}, \varepsilon_{22},\) and \(\varepsilon_{33}\) are major strains.

(4) Seepage equation
\[
K_{ij} \nabla^2 P_p \delta_{ij} = \frac{1}{Q} \frac{\partial P_p}{\partial t} - \alpha \frac{\partial \varepsilon_v}{\partial t}
\] (5)
where \(K_{ij}\) is the permeability, \(Q\) is Biot’s constant, and \(t\) is time.

(5) Coupling equation [35-37]
\[
K\left(\frac{\sigma_n}{3}, P_p\right) = \xi K_0 \exp\left[-\beta\left(\frac{\sigma_n}{3} - \alpha P_p\right)\right]
\] (6)
where \(K_0\) is the original permeability, \(K\) is the permeability, and \(\xi\) and \(\beta\) are material constants.
2.2. Meso-element model
The local mechanical properties (including Young’s modulus, Poisson’s ratio, and strength) of the elements are assumed to follow Weibull’s distribution because of the heterogeneity of formation [35-37]:

\[ \varphi(\omega, m) = \frac{m}{\omega} \left( \frac{\omega}{\omega_0} \right)^{m-1} \exp \left[ -\left( \frac{\omega}{\omega_0} \right)^m \right] \]  (7)

where \( \omega \) is the element property (Young’s modulus, Poisson’s ratio, or strength), \( \omega_0 \) is the mean value of \( \omega \) of the whole specimen, and \( m \) is a homogeneity index.

According to elastic damage mechanics, the failure of elements occurs when stress exceeds the strength of rock elements, and Young’s modulus after damage can be expressed as [35-37]

\[ E = (1 - D)E_0 \]  (8)

where \( E \) is the damaged Young’s modulus, \( E_0 \) is the undamaged Young’s modulus, and \( D \) is the damage variable that ranges from 0 to 1.

The elastic damage constitutive law of an element under uniaxial compression and extension is illustrated in Figure 1 [35-37].

![Figure 1. Elastic damage constitutive law under uniaxial compression and extension.](image)

(1) When the uniaxial tensile stress exceeds the tensile strength, element damage occurs; under this condition, this damage is described using the maximum tensile criterion [35-37]:

\[ \sigma_j = -f_{t0} \]  (9)

The damage variable is assigned as

\[ D = \begin{cases} 0 & \varepsilon \geq \varepsilon_{t0} \\ 1 - \frac{f_{t0}}{E_0 \varepsilon} & \varepsilon_{m} \leq \varepsilon < \varepsilon_{t0} \\ 1 & \varepsilon \leq \varepsilon_{m} \end{cases} \]  (10)

where \( f_{t0} \) is the residual tensile strength, \( \varepsilon_{t0} \) is the strain at the elastic limit, and \( \varepsilon_{m} \) is the ultimate tensile strain of the element.

(2) When the compressive stress exceeds the shear strength, element damage occurs; in this case, element damage is described using the Mohr–Coulomb criterion [35-37]:

\[ F = \sigma_1 - \sigma_3 \frac{1 + \sin \phi}{1 - \sin \phi} \geq f_{c} \]  (11)
The damage variable is assigned as

\[
D = \begin{cases} 
0 & \varepsilon < \varepsilon_{c0} \\
1 - \frac{f_{cr}}{E_0\varepsilon} & \varepsilon \geq \varepsilon_{c0}
\end{cases}
\]

where \( f_{cr} \) is the residual compressive strength, and \( \varepsilon_{c0} \) is the compressive strain at the elastic limit.

2.3. Model verification

The uniaxial compressive testing results of Longmaxi shale with different coring angles were obtained from a previous study [38], and the coring angles (angle \( \beta \) between the bedding plane and the x-axis) were \( 0^\circ, 15^\circ, 30^\circ, 45^\circ, 60^\circ, 75^\circ, \) and \( 90^\circ \). The testing results are shown in Figure 2. The Longmaxi shale has an average bedding thickness of 0.2 mm (ranging from 0.12 mm to 0.48 mm), and the numerical model proposed by the F-RFPA\(^{2D} \) code is illustrated in Figure 3; this model consists of 20,000 elements, and the meso-mechanical parameters are listed in Table 1 [38]. The numerical simulation results are presented in Figure 4. The simulated results of uniaxial compressive strength with different coring angles agree with the experimental results. In most cases, the relative error is less than 15%. The causes of this error mainly include two aspects: the heterogeneity of shale rock and the uncertainty of model parameters.

![Figure 2. Stress–strain curves of the layered shale rock with different coring angles.](image)

![Figure 3. Numerical model of the layered shale rock under uniaxial compression.](image)
Table 1. Parameters used in simulation in the F-RFPA\textsuperscript{2D} code.

| No. | Parameters                        | Rock matrix | Bedding |
|-----|----------------------------------|-------------|---------|
| 1   | Elastic modulus ($E_0$)          | 60 GPa      | 30 GPa  |
| 2   | Poisson’s ratio ($\nu$)          | 0.2         | 0.3     |
| 3   | Compressive strength ($\sigma_c$)| 330 MPa     | 220 MPa |
| 4   | Internal friction angle ($\phi$) | 53°         | 37°     |
| 5   | Maximum tensile strain           | 1.5$\mu$e   | 1.5$\mu$e |
| 6   | Maximum compressive strain       | 200$\mu$e   | 200$\mu$e |
| 7   | Homogeneity index ($m$)          | 2           | 3       |

Figure 4. Comparison of the experimental and numerical simulation results.

2.4. Numerical modeling

The F-RFPA\textsuperscript{2D} code was utilized to propose four typical numerical cases to simulate the fracture propagation in the vicinity of the borehole (Figure 5):

Figure 5. Four typical numerical models of F-RFPA\textsuperscript{2D}.

(1) Case 1 has a non-layered heterogeneous formation with a drilling-induced fracture, as shown in Figure 5(a). This formation is made of a heterogeneous rock and has a preset drilling-induced fracture, but it has no bedding planes and no natural fracture.
(2) Case 2 has a layered heterogeneous formation without a natural fracture, as illustrated in Figure 5(b). The formation is composed of a heterogeneous rock with bedding planes and a preset drilling-induced fracture, but it does not have a natural fracture.

(3) Case 3 has a non-layered heterogeneous formation with a natural fracture, as presented in Figure 5(c). The formation is a heterogeneous rock with a natural fracture (fracture length of 10 cm) and a preset drilling-induced fracture, but it has no bedding planes.

(4) Case 4 has a layered heterogeneous formation with a natural fracture, as described in Figure 5(d). The formation is a heterogeneous rock with bedding planes, a natural fracture (fracture length of 10 cm), and a preset drilling-induced fracture.

The present model consists of 230,400 elements (480×480), and the meso-mechanical parameters are listed in Table 1. The maximum horizontal in situ stress is 15 MPa, the minimum horizontal in situ stress is 10 MPa, the permeability is 0.0002 mD, the pore pressure coefficient is 0.6, and the tension-to-compression ratio is 10.0.

3. Results and discussion

3.1. Simulation results of case 1: Impact of heterogeneity

The simulation results of the non-layered heterogeneous formation without a natural fracture are shown in Figure 6. When the drilling-induced fracture exists, the wellbore fractures initially form and propagate along the direction of the maximum horizontal principal stress for the non-layered heterogeneous formation. The induced fracture begins to occur when the wellbore pressure gradually increases from 0 MPa to 36.26 MPa. It continues to propagate on a large scale when the wellbore pressure increases to 48.02 MPa. Some bifurcate fractures exist because of the heterogeneity of rock formation. In other words, a fracture network easily forms through heterogeneity formation.

![Figure 6. Fracture propagation in the vicinity of the borehole for case 1.](image)

3.2. Simulation results of case 2: Impact of heterogeneity and bedding planes

The simulation results of the layered heterogeneous formation without a natural fracture are illustrated in Figures 7–9. In this case, the bedding plane angles are 0°, 45°, and 90°. The results indicate that the existing bedding planes significantly influence fracture propagation in the vicinity of the borehole. As such, the fracture in the vicinity of the borehole easily propagates along the bedding planes, especially non-vertical bedding planes, as shown in Figures 7(c) and 8(c). Some bifurcate fractures exist at the fracture tip when the bedding planes are involved. Thus, the influence of bedding planes on the fracture propagation in the vicinity of the borehole cannot be ignored for lost circulation.
3.3. Simulation results of case 3: Impact of heterogeneity and natural fracture

The simulation results of the non-layered heterogeneous formation with a natural fracture are shown in Figure 10. The existing natural fracture significantly affects the fracture propagation in the vicinity of the borehole. This fracture easily changes its path along the natural fracture because of heterogeneity and natural fracture. Fracture propagation begins at the tip of the preset drilling-induced fracture regardless of the existence of the natural fracture. An obvious deflection also occurs at the initial stage of fracture propagation and gradually extends to the natural fracture location. When the natural fracture is vertical, as described in Figure 10(a), the induced fracture extends to, intersects with, and passes through the natural fracture. Thus, a complex fracture network easily forms. When the natural fracture is non-vertical, as displayed in Figures 10(b)–10(c), the induced fracture penetrates along and
bypasses the natural fracture but does not penetrate the natural fracture. Thus, the influence of heterogeneity and natural fracture on fracture propagation cannot be ignored for lost circulation.

![Figure 10](image)

(a) Natural fracture angle of 90° (b) Natural fracture angle of 60° (c) Natural fracture angle of 30°

**Figure 10.** Fracture propagation in the vicinity of the borehole for case 3.

3.4. **Simulation results of case 4: Impact of heterogeneity, bedding planes, and natural fracture**

The simulation results of the layered heterogeneous formation with a natural fracture are shown in Figure 11. In this case, the bedding plane angle and the natural fracture angle are 0° and 30°, respectively. The fractures extend along the direction of parallel bedding planes. Although an obvious deflection occurs during the connection between the fracture tip and the natural fracture tip, the existence of natural fracture does not change the effective propagation direction of fractures in case 4. In other words, the influence of bedding planes on fracture propagation in the vicinity of the borehole may be higher than that of the natural fracture for horizontal bedding planes (bedding plane angle of 0°). Therefore, the influence of bedding plane must be considered in the analysis of fracture propagation in the vicinity of the borehole, but the influence of natural fracture should be considered depending on actual needs.

![Figure 11](image)

(a) $P_w = 33.2$ MPa (b) $P_w = 34.3$ MPa (c) $P_w = 35.3$ MPa

**Figure 11.** Fracture propagation in the vicinity of the borehole for case 4 (bedding plane angle of 0° and natural fracture angle of 30°).

4. **Conclusions**

The F-RFPA$^{2D}$ code was utilized to simulate the fracture propagation in the vicinity of a borehole in terms of the influence of heterogeneity, natural fracture, and bedding planes, and the following conclusions can be drawn:

1. The numerical simulated results of the uniaxial compressive strength of Longmaxi shale are consistent with the experimental results. In most cases, the relative error is less than 15%. Thus, the F-RFPA$^{2D}$ numerical model is sufficiently precise for rock failure prediction.

2. Heterogeneity, bedding planes, and natural fracture significantly affect fracture propagation in the vicinity of boreholes. In the presence of these factors, a fracture network easily forms in the
vicinity of a borehole. Thus, their influence should be considered for the analysis and treatment of lost circulation.

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