An Integrated Method for Evaluating Lost Circulation Risk for Shale Gas Drilling in Sichuan Basin

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Abstract. Accurate prediction of lost circulation fracture width and lost circulation pressure is the basis for preventing lost circulation and curing the losses. They are controlled by many factors, such as in-situ stress, wellbore fluctuating pressure, rock properties, natural fractures, and so on. Researchers have put forward a variety of calculation models of lost circulation pressure for fractured formations; however, in the field practice, it is still mainly based on the minimum horizontal principal stress. The lost circulation of fractured formation seriously jeopardizes the safety and progress of drilling and production. At present, the success rate of curing the losses is low, one of the important reasons is that the fracture width cannot be accurately predicted. It is difficult to determine the wellbore strengthening method and particle size of the lost circulation materials due to unknown fracture width. Various prediction models of fracture width are used to calculate the fracture width of the loss layer, and the influence of the factors such as the loss time, drilling fluid properties (viscosity and yield value), and the angle between the fracture and the wellbore on the calculated fracture width is studied. For the lost circulation pressure, the acceptable loss rate in the drilling process is given. On the premise of the calculated fracture width, the lost circulation pressure under the acceptable loss rate is determined. The results show that the values of fracture width and lost circulation pressure predicted by the three methods are close to each other, and the prediction results of the three methods can be averaged in the field application to provide reference for the following work. The fracture width is sensitive to drilling fluid viscosity, bottom hole pressure, and other parameters, so the value of these parameters should be accurately measured in the field to reduce the uncertainty. The results also show that the larger the angle between fracture and wellbore, the more serious the lost circulation will be.

1. Introduction
Lost circulation refers to the phenomenon that drilling fluid flows into the formation through the lost circulation channel during drilling[1]. Usually, lost circulation occurs in the formation with well-developed pores and fractures. Therefore, according to the characteristics of lost circulation formation and the causes of lost circulation, lost circulation can be divided into four categories, namely, permeability loss, cavern loss, natural-fracture loss, and induced-fracture loss. According to statistics, the lost circulation problem in fractured formation accounts for more than 90% of the lost circulation events. Fractured formation usually has the characteristics of strong heterogeneity, strong stress sensitivity, multiple sets of pressure systems in the same well section, low lost circulation pressure gradient, and so on[2]. Complex geological conditions cause drilling fluid loss in the drilling process and delay oil and gas production, resulting in low economic benefits. Lost circulation has become a major engineering and technical problem in oilfield production[3]. The accurate prediction of fracture
width and lost circulation pressure is the premise of dealing with lost circulation[4]. In order to solve the problem of lost circulation, it is the key to find the cause of lost circulation, understand the fracture behaviour, and predict the fracture width and lost circulation pressure accurately [5].

2. Geological settings of the study area
In the process of drilling in a low porosity and low permeability shale gas block, in Sichuan Basin, there exist a lot of natural fractures in the shale reservoir. The existence of natural fractures leads to serious lost circulation problems. See Table 1 for the lost circulation events of the study area.

| loss location/m | loss time/h | loss rate/m³/h | loss volume/m³ |
|----------------|-------------|----------------|---------------|
| 2198           | 2           | 5              | 10            |
| 2209           | 4.4         | 0.9            | 4 (self curing the losses) |

According to the field lost circulation data, the loss layer may be around 2200 m, and the abnormal values of acoustic, porosity, and permeability logging curves also appear in this section, which further reflects the approximate location of the loss layer (see Fig. 1). According to the classification of loss velocity, it is concluded that the lost circulation belongs to small loss. Because the fractures are developed in the study area, it is preliminarily judged that the cause of lost circulation may be natural-fracture loss.

![Fig. 1. Acoustic (AC), porosity (POR), and permeability (PERM) logs.](image)

3. Methods
In this study, SEM experiments, well logging data, and drilling reports are used to evaluate lost circulation in shale formation. The calculation of fracture width and lost circulation pressure can provide the basis for subsequent wellbore strengthening operation, and more accurately select the upper limit of safe mud density window.

3.1 SEM experiments
SEM experiment is a kind of image analysis technology, which is mainly used to study the mineral composition, pore type and genesis, pore structure, micro fracture, rock cementation degree and secondary change of rock on the micro scale. Through the SEM experiment on the core, the micro development of fracture can be more intuitively reflected.
3.2 The estimate of fracture width

Muskat [6] and Jones [7] have shown that the permeability \( k \) and the porosity \( \phi \) of a system of parallel fractures spread all over a reservoir are given by

\[
k = \frac{w^3}{24\delta}
\]

\[
\phi = \frac{w}{\delta}
\]

where \( w \) is the average width; \( \delta \) is the average spacing (the average distance between two fractures).

From the field data, \( \delta = 11 \text{m} \). According to the permeability logging data, the permeability is 51 md and 64 md, respectively, therefore the average width is 237.9 \text{um} and 256.6 \text{um} respectively. The value of the porosity is \( 2.1 \times 10^{-5} \) and \( 2.3 \times 10^{-5} \), respectively. Because of self-plugging effect at 2209 m (the formation permeability is relatively high and the drilling fluid is filtrated in the fracture surface to form filter cake, which plays a role in plugging), the fracture width and lost circulation pressure at 2198 m are mainly studied. See Table 2 for drilling fluid properties of the loss zone.

| Loss location/m | Mud density/g/cm\(^3\) | Viscosity/mPa·s | Yield value/Pa |
|-----------------|------------------------|-----------------|----------------|
| 2198            | 1.88                   | 56              | 10.22          |
| 2209            | 1.88                   | 56              | 10.22          |

There are three methods to predict the fracture width: Griffiths method, Sanfillippo method, and Verga method.

3.2.1 Griffiths method

Lietard [8] considered that the fluid flowing in the fracture is Bingham fluid (fracture model shown in Fig. 2), and the pressure gradient of the fluid flowing in the fracture is as follows:

\[
\frac{dp}{dr} = \frac{12\mu_p v}{w^2} + \frac{3\tau_y}{w}
\]

where \( \frac{dp}{dr} \) is the local pressure gradient; \( \mu_p \) is plastic viscosity; \( \tau_y \) is yield value; \( w \) is the fracture width; \( v \) is the loss rate.

![Fracture model](Fig. 2. Fracture model.)
Griffiths method puts forward the idea of maximum invasion radius \( R_{\text{max}} \) to solves Eq (3), and obtains the relationship between fracture width and pressure difference:

\[
\left( \frac{\Delta P}{r_w} \right)^2 w^3 + 6r_w \left( \frac{\Delta P}{r_w} \right) w^2 - \frac{9}{\pi} V_m = 0 \tag{4}
\]

where \( r_w \) is wellbore radius; \( \Delta P \) is pressure difference.

### 3.2.2 Sanfillippo method

The process of squeezing the mud into a single fracture (schematic diagram of intersection of wellbore and fracture is shown in Fig. 3) has been described through the diffusion equation in radial coordinates as follows [9]:

\[
\frac{\partial^2 P}{\partial r^2} + \frac{1}{r} \frac{\partial P}{\partial r} = \frac{\mu \Phi c_t}{k} \frac{\partial P}{\partial t} \tag{5}
\]

where \( \mu \) is the mud viscosity; \( \Phi \) is the fracture porosity; \( c_t \) is total compressibility, the compressibility of drilling fluid is approximately equal to that of water, \( c_t = 4 \times 10^{-4} \); \( k \) is permeability.

![Diagram of intersection of wellbore and fracture](image)

**Fig. 3.** Schematic diagram of intersection of wellbore and fracture (when \( \gamma = 0 \), it is horizontal fracture).

The diffusion equation is solved by interpolation with analytical function.

\[
c \frac{w^3 t}{12 \phi \mu c r_{eq}^2} - \frac{V_m}{2 \pi \phi c r_{eq}^2 w \Delta P} = 0 \tag{6}
\]

where \( c \) is the correction coefficient, generally 2.01; \( t \) is the loss time; \( r_{eq} \) is the equivalent radius of the elliptic surface of the intersection of fracture and wellbore.

Then,

\[
c \frac{\alpha w^2}{\ln(\alpha w^3)} - \frac{\beta}{w} = 0 \tag{7}
\]

where \( \alpha = \frac{t}{12 \phi \mu c r_{eq}^2} \), \( \beta = \frac{V_m}{2 \pi \phi c r_{eq}^2 \Delta P} \)

### 3.2.3 Verga method


Based on the diffusion equation adopted by Sanfillippo model, assuming that the drilling fluid radial inflow width is \( w \), the diffusion equation, namely Muskat formula, is solved under steady-state conditions [10]:

\[
\Delta p = \frac{6\nu \mu}{\pi w^3} \ln \left( \frac{V_m + r_w^2}{2r_w} \right)
\]

For every measurement of lost circulation, the root of Eq (4), (7) and (8) are computed through a numerical iteration using the Newton-Raphaon method.

### 3.3 The estimate of lost circulation pressure

For the fracture development section, the value of lost circulation pressure is usually lower than the value of the minimum in-situ stress commonly used in engineering design. For the fracture development section, an acceptable loss velocity can be given. Under the acceptable loss velocity, according to the value of fracture width calculated in the previous section, the acceptable flow pressure difference can be obtained by using the Eq (4), (7) and (8) in the previous section. Based on this, the value of lost circulation pressure in fracture development section is obtained [11].

\[
P_l = P_f + \Delta P
\]

where \( P_l \) is lost circulation pressure; \( P_f \) is the formation pressure; \( \Delta P \) is the acceptable pressure difference.

The loss velocity at 2209 m is 0.9 m\(^3\)/h, which can achieve the function of self-curing. Therefore, it is assumed that the acceptable loss velocity in engineering is 1 m\(^3\)/h.

### 4. Results

#### 4.1 SEM experiments

Through the SEM experiment, the micro fractures are developed in the formation, which further verifies that the cause of lost circulation is natural fractures. The experimental results are shown in Fig. 4.

![SEM pictures](image)

**Fig. 4.** SEM pictures.

#### 4.2 The effect of loss time

Other conditions remain unchanged, the values of fracture width under different loss time are calculated, and the results are shown in Fig. 5. The results show that the fracture width calculated by Griffiths method does not change with the change of loss time, while the fracture width calculated by Sanfillippo method and Verga method increases dynamically with the increase of time. Thus, the average fracture width calculated by Griffiths method cannot reflect the dynamic change process of...
fracture width with time, while the Sanfillippo method and Verga method can better reflect the dynamic change of fracture width.

![Graph](image1)

**Fig. 5.** Relationship between fracture width and loss time.

**4.3 The effect of viscosity**

Other conditions remain unchanged, the values of fracture width and acceptable difference pressure under different drilling fluid viscosities are calculated, and the results are shown in Fig. 6. The results show that the fracture width and acceptable pressure difference calculated by Griffiths method basically do not change with the change of viscosity. The fracture width and acceptable pressure difference calculated by Sanfillippo method and Verga method are very sensitive to the change of viscosity. Therefore, in order to predict the fracture width and acceptable pressure difference more accurately, it is necessary to measure the properties of drilling fluid more accurately, so as to reduce the prediction error.

![Graph](image2)

**Fig. 6.** The relationship between fracture width, acceptable pressure difference, and viscosity.

**4.4 The effect of angle \( \gamma \) between fracture and wellbore**

It can be seen from Fig. 7 that the larger the angle \( \gamma \) between wellbore and fracture is, the smaller the predicted fracture width will be. The analysis may be because the larger the angle \( \gamma \) is, the larger the elliptical surface intersecting the wellbore and fracture is, which increases the diffusion area. Because the loss volume is certain, the predicted fracture width becomes smaller. When the angle \( \gamma \) is less than 30°, the fracture width will be less affected. When the angle \( \gamma \) is greater than 30°, the fracture width decreases more obviously as the angle increases.
5. Discussions
Assuming that there is a known fracture (given fracture width of 390 um), the relationship between the angle of intersection of wellbore and fracture and loss rate and acceptable pressure difference is studied. The results are shown in Fig. 8.

The larger the intersection angle between wellbore and fracture is, the larger the diffusion area is. At the same time, the larger the loss volume is, the faster the loss rate is. In order to drill safely, the lost circulation pressure will also be reduced. Therefore, the wellbore should be drilled vertically to meet natural fractures, which may reduce the impact of lost circulation to a certain extent.

6. Conclusions
The fracture width prediction results of Griffiths method, Sanfillippo method and Verga method are relatively close, and the average value can be taken as the prediction basis in the field application. The predicted values of fracture width and lost circulation pressure are sensitive to the viscosity of drilling fluid, so it is necessary to accurately measure drilling fluid properties and reduce prediction error. The existence of angle $\gamma$ between fracture and wellbore will affect the predicted fracture width and lost circulation pressure. Given the acceptable lost circulation pressure difference in engineering, the drilling mud density window can be further expanded. In the above field case, the lost circulation pressure difference under the allowable loss rate expands the mud density window by about 0.2 g/cm$^3$. Therefore, on the premise that the fracture width is not too large, given the allowable loss rate, the calculated lost circulation pressure will expand the mud density window within a reasonable range and realize safe drilling.
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