INTRODUCTION

“Horizontal well + segmented multi-cluster perforation + large-displacement hydraulic fracturing” has led to the commercial development of unconventional reservoirs, especially of shale gas. The main and branch fractures formed during fracturing are the tensile fractures of the shale reservoir, whereas the secondary fractures are the shear misalignment fractures; all the fracture surfaces are rough. When the fracturing is completed, the fractures with proppant cannot be closed, and the unsupported fractures are relatively dislocated owing to the geostress and cannot be completely closed, thereby resulting in unpropped fractures. An unpropped fracture with conductivity is the basis of fluid flow in fracture networks (Appendix A–D).

Abstract

Hydraulic fracture is widely performed to enhance oil and gas production in the development of unconventional reservoirs. This paper proposes a numerical model for the calculation of the unpropped fracture conductivity of shale. This numerical model consists of three basic models, namely, the numerical reconstruction model of fracture morphology, fracture deformation model under closed stress, and fluid flow model. The numerical model can be used to analyze the influencing factors of the unpropped fracture conductivity of shale quantitatively. The results demonstrate that the fracture misalignment of shale is a prerequisite for unpropped fractures with conductivity at high closed stress. Furthermore, the unpropped fracture conductivity of shale decreases exponentially with the increase in closed stress. Moreover, closed stress is the factor having the most significant influence on the unpropped fracture conductivity of shale, followed by roughness and fracture morphology. The negative effect of closed stress can be reduced by increasing the fracture morphology during the fracturing operation.

KEYWORDS

closed stress, conductivity, fracture morphology, shale, unpropped fracture
Fracture conductivity refers to the ability of a fracture to fill a proppant to pass through a fluid under reservoir stress, which can be expressed by the fracture width multiplied by the fracture permeability. So far, the studies on unpropped fracture conductivity are primarily based on experiments, and the mathematical models are empirical formulas fitted according to the experimental results. For instance, Penny determined through experiments that time and temperature are the main factors influencing the decline in long-term conductivity. Van and De demonstrated experimentally that fractures without proppant still have conductivity even under closed stress. Numerous experiments that demonstrate that the fracture conductivity decreases exponentially with the increase in closed stress have been conducted.

Although experiments can simulate the formation state to obtain more accurate conductivity, there are several factors that influence the unpropped fracture conductivity of shale. Hence, it is difficult to conduct these experiments owing to the following reasons: (a) According to the American Petroleum Institute (API) standard, the shale sample is large in size (length: 178 mm, width: 38 mm), which makes processing difficult. (b) The experiment is time-consuming owing to the close correlation between the experimental steps. (c) There are several factors that affect the conductivity of shale (such as fluid properties, temperature, stress, initial fracture surface morphology, rock mechanical properties, and misalignment movement), making the analysis of the data difficult.

“Acid etching fracture conductivity” is another important method that can be used to study fracture conductivity. Nierode and Kruk proposed the Nierode-Kruk model for the quantitative evaluation of acid etching fracture conductivity. Based on this model, researchers have developed more accurate conductivity models (Table 1) considering factors such as closed stress, rock mechanical properties, and fracture surface roughness.

Table 1 indicates that the theoretical model of acid etching fracture conductivity is directly or indirectly related to the roughness and morphology of the fracture surface. Owing to the large difference in surface roughness between the acid etching fracture and unpropped fracture, the application of these models to calculate the unpropped fracture conductivity is limited. Therefore, the morphology and roughness of a fracture are vital in calculating the fracture conductivity of shale.

The fracture morphology comprises two parts: wall roughness and opened fracture surface. Tse et al. and Turk et al. proposed to reconstruct the rough-walled fracture surface using an interpolation method. However, this method is prone to errors due to frequent interpolation iterations. Lespinasse and Sausse used an automatic surface profilometer to measure the fracture surface roughness and consequently proposed a set of methods to describe the distribution of a rough-walled fracture. Issa and Hammad considered factors such as closed stress, rock mechanical properties, and fracture surface roughness.
observed that fracture wall surfaces generated by natural faults exhibit fractal characteristics. Therefore, the fractal dimension can be used to describe the fracture wall roughness. Brandt and Prokopski\textsuperscript{2} observed that the fracture roughness is proportional to the fractal dimension. Barton et al\textsuperscript{1} and Barton\textsuperscript{43} observed that the distribution of fracture width obeys the lognormal and negative exponential distributions.

The unpropped fracture conductivity of shale is also affected by vertical stress.\textsuperscript{13} Studies have shown that loading effective stresses on the fractures can significantly change the fracture width and the fluid velocity and pressure distribution within the fracture.\textsuperscript{4,5,40} A rough-walled fracture can be deformed by vertical stress, thereby reducing the fluid flow ability of the fracture.\textsuperscript{22} Subsequently, Louis\textsuperscript{17} proposed that vertical stress can be more accurately expressed using “effective stress.” He established an exponential relationship between effective stress and flow coefficient.\textsuperscript{17} Scholars have always hoped to describe the relationship between stress and fluid flow in fractures quantitatively through a mathematical model, however, most models are empirical formulas obtained via fit and regression according to the experimental data.

Unpropped fractures of shale have characteristics of large size, high roughness, and random morphology.\textsuperscript{21} Thus, the Navier-Stokes equation is often used to study the fluid flow in fractures.\textsuperscript{5} To simplify the calculation, the inertial force is often neglected, and the nonlinear three-dimensional (3D) Navier-Stokes equation is reduced to a linear 3D model.\textsuperscript{42} However, when the Reynolds number is too large, the inertial force cannot be neglected, and the nonlinear 3D Navier-Stokes equation cannot be simplified to ensure calculation accuracy.\textsuperscript{14} The 3D model is approximated to a two-dimensional model by using the “regular discrete fracture morphology model” under uniform fracture width.\textsuperscript{16} When the rough-walled fracture length is greater than five times the fracture width, the error between the simplified model and the Navier-Stokes equation is $>10\%$.\textsuperscript{41}

The Navier-Stokes equation has considerable limitations in the study of rough-walled fracture morphology. The Lattice Boltzmann (LBM) discrete numerical simulation method can effectively match the geometry of rough-walled fractures and examine the law of fluid motion.\textsuperscript{31,37} The LBM method discretizes fluid particle motion comprising two main steps: migration and collision.\textsuperscript{36} Migration is the conversion of particles from one node to the next on the grid. Collisions preserve the momentum by redirecting “collisions” or particles that occupy the same node. Marty and Hagedorn\textsuperscript{18} improved the LBM to make it easier to describe node velocity and fluid momentum through probability distribution functions.

In this paper, based on the fracture shear slip and characteristics of rough-walled fractures, we proposed a rough-walled fracture numerical restructure model. Additionally, we proposed a fracture deformation model under closed stress based on the mechanical characteristics of shale. We adopted the 3D LBM method to establish the fluid flow model in rough-walled fractures. We constructed a mathematical model to calculate the unpropped fracture conductivity of shale using the joint fracture numerical restructure model, fracture deformation model under closed stress, and fluid flow model. The shale used in this study was obtained from Longmaxi Formation in the south of the Sichuan Province to verify the correctness of the numerical model.

## 2 | MATHEMATICAL MODEL

The mathematical model used for the calculation of the unpropped fracture conductivity consists of a numerical reconstruction model of fracture (Appendix A), fracture deformation model under closed stress (Appendix B), and fluid flow model (Appendix C), as illustrated in Figure 1.

### 2.1 | Numerical reconstruction model of fracture

The height matrices of the upper and lower fracture surfaces after misalignment are expressed as Equations 1 and 2, respectively.

The height division for the upper surface of the fracture is expressed by Equation 1:

\[
\begin{align*}
A_i &= (a_{ij}), (i = 1, 2, 3, \ldots; m; j = 1, 2, 3, \ldots, n) \\
A'_{ij} &= (a'_{ij}) = (a_{ij} - \min (a_{ij})), (i = 1, 2, 3, \ldots; m; j = 1, 2, 3, \ldots, n) \\
A_{ij} &= (a''_{ij}) = \left[ a'_{ij} - \min (a'_{ij}) \right] \left[ a'_{ij} - \max (a'_{ij}) \right], (i = 1, 2, 3, \ldots; m; j = 1, 2, 3, \ldots, n) \\
A_{SDIS} &= (a_{SDIS(i,j)}) = (a_{ij}), (i = 1, 2, 3, \ldots; m; j = 1, 2, 3, \ldots, n; \delta) \\
Z_i &= (z_{SDIS}) = (a_{SDIS} - \min (a_{SDIS})), (i = 1, 2, 3, \ldots; m; j = 1, 2, 3, \ldots, n - \delta) \\
\end{align*}
\]

The height division for the lower fracture surface is expressed by Equation 2:

\[
\begin{align*}
A_i &= (a_{ij}), (i = 1, 2, 3, \ldots; m; j = 1, 2, 3, \ldots, n) \\
A'_{ij} &= (a'_{ij}) = \left[ a_{ij} - \min (a_{ij}) \right], (i = 1, 2, 3, \ldots; m; j = 1, 2, 3, \ldots, n) \\
A_{ij} &= A'_{ij} \\
A_{SDIS} &= (a_{SDIS(i,j)}) = (a_{SDIS}), (i = 1, 2, 3, \ldots; m; j = 1, 2, 3, \ldots, n - \delta) \\
Z_i &= (z_{SDIS}) \\
\end{align*}
\]

where $A$ represents the initial height matrices of fracture obtained via laser scanning; $Z$ is the height matrix of fracture after misalignment; $a$ is the element of the matrix; $A'_{0k}$ is the vertical-reverse height division of the upper fracture surface; $A_{0s}$ is the symmetric placement matrix; the subscripts 0, 1 and $u$, $d$ represent the upper and lower surfaces of the fracture, respectively; SDIS indicates a fracture having misalignment movement.
2.2 | Fracture deformation model under closed stress

The morphology of the unpropped fracture under closed stress can be expressed by Equations 3 and 4.

\[
\begin{align*}
Z_1 &= \max (z_{uij} - z_{adj}), (i = 1, 2, 3, \ldots m; j = 1, 2, 3, \ldots n - \delta) \\
Z_2 &= Z_d \\
Z_u' &= (z_{uij} - Z), (i = 1, 2, 3, \ldots m; j = 1, 2, 3, \ldots n - \delta) \\
Z_c &= Z_d - Z_u' \\
\Delta Z &= (\Delta z_{ij}) = \begin{cases} 
0, & z_{cij} \geq 0 \\
|z_{cij}|, & z_{cij} \leq 0
\end{cases}
\end{align*}
\]

Here, \(Z_1\) and \(Z_2\) represent the microelement height matrices of the upper and lower surfaces of the fracture, respectively; \(Z_u'\) represents the height division after the upper surface of the fracture moves down; \(Z_c\) represents the height division after fracture deformation; \(\Delta Z\) represents the compression deformation matrix.

By substituting Equation 4 into 5, the relationship \(\sigma = f(Z)\) between the closed stress and fracture morphology can be obtained via cyclic calculation as follows:

\[
\sigma = \sum_{i=1}^{m} \sum_{j=1}^{n-\delta} \left\{ \begin{array}{l}
\Delta z_{1ij} \left( \frac{u^2}{z_{1ij}} + \frac{v^2}{z_{2ij}} \right) + \Delta z_{2ij} \left( \frac{2z_{1ij}u^2}{z_{1ij}} + \frac{3\Delta z_{2ij}u^2 + 2z_{2ij}v^2}{z_{2ij}} \right) \\
\frac{z_{2ij}^2 \Delta z_{2ij} + 2z_{2ij}v^2 \Delta z_{2ij} + v^2 \Delta z_{2ij}}{z_{2ij}} = 0
\end{array} \right.
\Delta f_{cij} = \frac{\Delta z_{1ij}E \left( X + \frac{v \Delta z_{1ij}}{z_{ij}} \right)^2}{z_{1ij}}
\sigma_{0ij} = \frac{\Delta F_{cij} z_{1ij}^2}{2z_{1ij}}
\sigma_{ij} = \begin{cases} 
\sigma_{0ij}, & \sigma_0 \leq \sigma_m \\
\sigma_m M_c, & \sigma_0 \geq \sigma_m
\end{cases}
\]

where \(E, v, \) and \(\sigma_m\) represent Young’s modulus, Poisson’s ratio, and the compressive strength of shale, respectively.

If the closed stress on shale is known, then the fracture width can be expressed by Equation 6.

\[
W_f = (w_{fj}) = \begin{cases} 
z_{cij} \Delta z_{ij} \geq 0 \\
0, & \Delta z_{ij} \leq 0
\end{cases}
\]

where \(W_f\) is the fracture width, \(m\).

2.3 | Fluid flow model

According to the height division of the lower fracture surface, \(Z_d\), under closed stress and deformation, and the corresponding fracture width distribution matrix, \(W_f\), a physical model for the LBM flow field calculation was constructed. The meshing of the LBM flow field was obtained via cyclic calculation as follows:

First, the discrete velocity is expressed by Equation 7:

\[
c_a = \begin{cases} 
(0,0,0)c, & a = 0 \\
(\pm 1,0,0)c, & (0,0,0)c, (0,0, \pm 1)c, a = 1,2,..., 6 \\
(\pm 1, \pm 1,0)c, & (\pm 1,0, \pm 1)c, (0, \pm 1, \pm 1)c, a = 7,8,..., 18
\end{cases}
\]

The equilibrium distribution function is expressed by Equation 8:

\[
f_a^{eq} = w_a \rho \left[ 1 + \frac{(c_a \cdot u^{eq})}{\epsilon_s^2} + \frac{(c_a \cdot u^{eq})^2}{\epsilon_s^4} - \frac{(u^{eq} \cdot u^{eq})}{\epsilon_s^2} \right] + \Delta z_{1ij} \left( \frac{1}{z_{1ij}} + \frac{z_{1ij}^2 + 4v \Delta z_{1ij} z_{2ij} + 3 \Delta z_{2ij} v^2}{z_{2ij}} \right)
\]

where \(w_a\) is the weight coefficient, which is related to the velocity component and can be expressed by Equation 10.

\[
w_a = \begin{cases} 
1/3, & a = 0 \\
1/18, & a = 1,2,..., 6 \\
1/36, & a = 7,8,..., 18
\end{cases}
\]
The solid-liquid interface is set as the standard bounce format, and the fluid boundary is set as the gravity-driven periodic boundary. After calculating the equilibrium distribution at each particle density, the particle collision and migration are calculated by Equations 11 and 12, respectively, and a new density distribution function is generated.

The collision calculation function is expressed by Equation 11:

\[
\bar{f}_i(x, t) = f_i(x, t) - \frac{1}{\tau} \left[ f_i(x, t) - f_i^{(eq)}(x, t) \right] \tag{11}
\]

The transfer calculation function is expressed as follows:

\[
\tilde{f}_i(x, t + \delta t) = \tilde{f}_i(x, t) \tag{12}
\]

where \( \tilde{f}_i(x, t) \) and \( f_i(x, t) \) are the density distribution functions of the fluid after collision and in the current state, respectively; \( f_i^{(eq)}(x, t) \) is the density distribution function of the fluid at equilibrium; \( \tau \) is the dimensionless relaxation factor.

**FIGURE 1** Mathematical model calculation of unpropped fracture conductivity

**FIGURE 2** Flowchart of the process of solving the unpropped fracture conductivity model
2.4 | Numerical model solution

Figure 2 depicts the sequence of the process of solving the unpropped fracture conductivity numerical model, which can be described as follows:

- The fracture surface is scanned using a laser to obtain data \( A_0 \) and \( A_1 \).
- The initial unpropped fracture surface morphology is determined based on the fracture surface data and misalignment.
- According to the Young’s modulus and Poisson’s ratio of the shale, the initial unpropped fracture of the shale is subjected to the fracture deformation model, and the stress-misalignment chart is obtained.
- The deformation is determined in the stress-misalignment chart, according to the closed stress.
- The initial fracture is subjected to deformation calculation to obtain the fracture morphology.
- The LBM method is used to mesh and simulate the fractures after deformation, the fracture permeability under closed stress can be subsequently obtained, and the fracture conductivity at any point can be calculated according to API RP 19D-2008.

3 | MODEL EXPERIMENTAL VERIFICATION

3.1 | Experiment

We evaluated the conductivity of two shale samples (sample 1 and sample 2) selected from the Longmaxi Formation in the Sichuan Basin with different surface roughnesses to verify the accuracy of the numerical model of the unpropped fracture conductivity. The surface of sample 1 is smoother than that of sample 2, and the mechanical properties of the two samples are listed in Table 2.

| Sample | Young’s modulus (MPa) | Poisson’s ratio | Compressive strength (MPa) |
|--------|-----------------------|----------------|--------------------------|
| 1^#    | 27 674.6              | 0.234          | 290.8                    |
| 2^#    | 24 031.3              | 0.216          | 290.3                    |

A “self-supporting fracture test analysis device”\(^3\) was used to test the unpropped fracture conductivity. The experimental steps are as follows:

- A shale sample was prepared with a length of 176.0 mm and a width of 36.0 mm.
- The sample was divided into two pieces along its natural fracture.
- The upper and lower rock plates of the sample were dislocated by 2.5 mm, and then, they were integrally fixed with tape and sealed with Vaseline.
- The rock sample was placed in the test device. A leakage pressure test was performed by applying an injection pressure of 5 MPa and a back pressure of 3 MPa.
- The conductivity test chamber was heated at 3°C/min, the closed stress was applied to the rock sample at 6 MPa/min, and then, nitrogen was slowly injected at 100 mL/min.
- The experimental data were recorded when the closed stress, temperature, and flow rate of nitrogen reached a steady state.

3.2 | Numerical reconstruction of fracture morphology

The fracture surface was numerically reconstructed using the upper and lower fracture surface height matrices (Equations 1 and 2, respectively) and the surface data. The results are shown in Figure 3. Sample 1 and Sample 2 are two typical features of shale. It can be observed from the color distribution (Figure 3) that the height of the fracture surface of sample 1 is not as evident as that of sample 2. This indicates that the fracture surface of sample 1 is smoother than that of sample 2. If the fractures are misaligned to form an unpropped fracture, then the unpropped fracture of sample 2 would be more evident than that of sample 1.

The distribution of fracture width directly reflects the internal space structure of the fracture. The numerical reconstruction model (Equations 1 and 2) is used to reconstruct the fracture surface with a misalignment of 2.5 mm. The distribution cloud of the misalignment fracture and the distribution frequency of the fracture width are shown in Figure 4. The fracture width distribution frequencies of the two samples demonstrate a single peak, and the distribution of fracture width is concentrated, demonstrating a normal distribution. The misalignment fracture width of sample 1 is mainly concentrated in the range of 1.019-2.719 mm, whereas the fracture width of sample 2 is mainly concentrated in the range of 1.921-5.766 mm. The misalignment fracture of sample 2 provides a more convenient passage for fluids to flow therein.

3.3 | Calculation of fracture deformation under closed stress

Based on the fracture deformation model under different closed stresses (Equation 5), we obtained the relationship between the deformation and closed stress of the rock samples, as illustrated in Figure 5. The stress-deformation curve of a
fracture has three phases: (a) In the first stage, the deformation increases sharply with the increase in closed stress under lower stresses. (b) In the second stage, as the closed stress increases, the deformation tends to increase linearly. (c) In the third stage, the fracture deformation increases sharply with the increase in closed stress. Combined with the initial fracture width distribution frequency (Figure 4), owing to the narrow distribution of the fractures, the contact points are concentrated, and the microbody rapidly reaches the yield condition and then deforms as the closed stress increases. As the closed stress increases, more convex points come in contact with the rough fracture surface, and the relationship between the fracture deformation and closed stress demonstrates a linear change. More support points reach the yield state with the continuous increase in closed stress owing to the decrease in the number of wide parts, thereby sharpening the fracture width (Figure 5). The distribution of the fracture under different closed stresses is shown in Figure 6.

3.4 | Comparison of calculation and experimental results

The numerical reconstruction model of fracture, fracture deformation model under closed stress, and 3D LBM model are used to calculate the unpropped fracture conductivity of shale with a 0.2-mm grid, and the comparison of the calculation and experimental results is illustrated in Figure 7. The fluid medium used for calculation is nitrogen gas with a viscosity of $17.85 \times 10^{-3}$ mPa·s and density of 1.25 kg/m$^3$ for low-speed flow. As illustrated in Figure 7, the misalignment of the unpropped fracture of shale is a prerequisite for its conductivity under high closed stress ($\geq 4$ MPa); the unpropped fracture conductivity decreases exponentially with the increase in the closed stress. This law of unpropped fracture conductivity is consistent with that of sandstone and the previous experimental results for shale.6,9

The unpropped fracture conductivity obtained using the numerical reconstruction model of fracture, fracture deformation model under closed stress, and LBM model is consistent with the reducing trend of that obtained via experimental tests, as shown in Figure 7. However, under low closed stress, the calculation accuracy is higher than that under high closed stress; furthermore, the calculation accuracy for wide fractures is higher than that for narrow fractures. For example, when the closed pressure is 1 MPa, the errors between the experimental and calculated results of unpropped fracture conductivity of samples 1 and 2 are only 4.51% and 4.17%, respectively. However, when the closed stress increases to 45 MPa, the errors of samples 1 and 2 increase to 40.16% and 22.08%, respectively. This is because, under high closed stress, the width of the partial fracture is smaller than the mesh size (0.2 mm) used for the LBM calculation. When using a 0.2-mm cube mesh for calculation, the wide fracture has a larger number of compute nodes, and hence, the calculation accuracy is higher. When the physical model has a constant size, the calculation accuracy can be improved by reducing the mesh size.

4 | INFLUENCE FACTORS OF CONDUCTIVITY

Several factors affect the unpropped fracture conductivity of shale. To consider the impact of various factors fully, we first use the orthogonal analysis method to design the
calculation program; then, we use the conductivity numerical calculation model to calculate the unpropped fracture conductivity of shale; finally, the influence law of each factor is analyzed using the range summation method of the statistics (Appendix D). The higher the bit level of a certain influencing factor, the greater is the unpropped fracture conductivity. A grid of 0.2 mm is selected for low closed stresses (1-4 MPa) and a 0.1-mm grid is selected for high closed stresses (≥4 MPa) to ensure the accuracy and efficiency of the calculation results.

4.1 Fracture surface roughness

The effect of fracture surface roughness on the unpropped fracture conductivity demonstrates an increasing trend first and then a decreasing trend, as shown in Figure 8. When the fracture surface roughness is 2.7-2.8, the range summation is at its maximum. This indicates that, when the fracture surface roughness is 2.7-2.8, the conductivity of fracture is at its highest. When the fracture surface roughness value is too small, the fracture is smooth, and it is not easy to form an unpropped fracture; thus, the range summation is small. However, when the fracture surface roughness value is too high, the fracture width decreases under closed stress, which leads to a decrease in the conductivity. Therefore, the range summation decreases when the roughness value is too high.

4.2 Misalignment

It can be observed from Figure 9 that, when the fracture morphology is less than 4 mm, the range summation increases...
with the fracture morphology. When the fracture morphology is 4 mm, the range summation decreases slightly. When the fracture morphology reaches 4 mm, the tops of the support points on the fracture surfaces are in contact with each other, and the unpropped fracture conductivity is at its highest, indicating that the bit-value summation is at its highest. If the fracture morphology is further increased, the range summation will decrease owing to the decrease in the fracture width.

4.3 | Closed stress

As can be observed from Figure 10, the range summation decreases with the increase in closed stress. When the closed stress increases from 1 MPa to 10 MPa, the range summation decreases by 307.5/MPa. When the closed stress increases from 10 MPa to 30 MPa, the range summation decreases by 51.6/M Pa. This is consistent with the exponential decrease in the unpropped fracture conductivity with the increase in closed stress.
**FIGURE 8** Effect of fracture surface roughness

![Graph showing the effect of fracture surface roughness.](image)

**FIGURE 9** Effect of fracture morphology

![Graph showing the effect of fracture morphology.](image)

**FIGURE 10** Effect of closed stress

![Graph showing the effect of closed stress.](image)
4.4 | Rock mechanical properties

The influence of the mechanical properties of shale such as Young's modulus, Poisson's ratio, and compressive strength on the unpropped fracture summation is shown in Figure 11. It can be observed from the figure that the range summation demonstrates no regularity with the change in the rock mechanical properties. This indicates that the mechanical properties...
properties of shale have an irregular effect on the unpropped fracture conductivity of shale. Moreover, the mechanical properties of shale have a much weaker effect on the conductivity than that of roughness, misalignment, and closed stress.

4.5 | Order of influence factors

We use the range (maximum range summation of influencing factor minus the minimum range summation) to evaluate the effect degree of each influencing factor and to identify the key factors affecting the unpropped fracture conductivity of shale. The results are illustrated in Figure 12. The influence of various factors on the unpropped fracture conductivity of shale can be ranked as follows: closed stress > fracture surface roughness > misalignment > compressive strength > Young’s modulus > Poisson’s ratio. Closed stress has the most significant influence on the unpropped fracture conductivity of shale; thus, the influence of closed stress must be considered during the design of the fracturing process.

5 | CONCLUSIONS

In this study, a numerical model of unpropped fracture conductivity of shale was proposed, and it was verified through shale fracture conductivity tests. This numerical model was based on the numerical reconstruction model of fracture, fracture deformation model under closed stress, and 3D LBM model. Furthermore, the numerical model of unpropped fracture conductivity was used to analyze the influencing factors of the unpropped fracture conductivity of shale. The main findings are as follows:

- Misalignment of shale is a prerequisite for the unpropped fracture with conductivity at high closed stresses (≥4 MPa).
- The influence of various factors on the unpropped fracture conductivity of shale can be ranked as follows: closed stress > fracture surface roughness > misalignment > compressive strength > Young’s modulus > Poisson’s ratio.
- The unpropped fracture conductivity of shale decreases exponentially with the increase in closed stress.
- The effect of closed stress can be reduced by increasing the fracture morphology during the fracturing operation.

ACKNOWLEDGMENTS

This article was prepared under the auspices of the State Key Laboratory of Oil and Gas Reservoir Geology and Exploitation at Southwest Petroleum University. And supported by National Natural Science Foundation of China (51704251, 51525404), and National Science and Technology Major Project of the Ministry of Science and Technology of China (2016ZX05006002).

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REFERENCES

1. Barton N, Bandis S, Bakhtar K. Strength, deformation and conductivity coupling of rock joints. *Int J Rock Mech Mining Sci Geomech Abs*. 1985;22:121-140.
2. Brandt AM, Prokopski G. On the fractal dimension of fracture surfaces of concrete elements. *J Mater Sci*. 1993;28:4762-4766.
3. Jianchun G, Xinghao G, Cong L, Chao L, Chi C. Unpropped crack test device and method for oil and gas field development. China National Invention Patent, ZL201210239135.4, July 11, 2012. In: China National Intellectual Property Administration.
4. Chen T, Feng X-T, Cui G, Tan Y, Pan Z. Experimental study of permeability change of organic-rich gas shales under high effective stress. *J Nat Gas Sci Eng*. 2019;64:1-14.
5. Cui G, Liu J, Wei M, Shi R, Elsworth D. Why shale permeability changes under variable effective stresses: New insights. *Fuel*. 2018;213:55-71.
6. Deng J, Mou J, Hill AD, Zhu D. A New Correlation of Acid Fracture Conductivity Subject to Closure Stress. *SPE Hydraulic*

FIGURE 12 Range of influencing factors on the unpropped fracture conductivity of shale
6. Tse R, Cruden DM, England KW. Estimating joint roughness coefficients. *Int J Rock Mech Mining Sci Geomech Abst.* 1979;16:303-307.
7. Turk N, Dearman WR. Improvements in the determination of point load strength. *Ball Int Assoc Eng Geol.* 1985;31:137-142.
8. Van DD, De PC. Roughness of hydraulic fractures: importance of in-situ stress and tip processes. *SPE Journal.* 2001:6-4-13.
9. Walsh JB. Effect of pore pressure and confining pressure on fracture permeability. *Int J Rock Mech Mining Sci Geomech Abst.* 1981:18:429-435.
10. Wang J, Chen L, Kang Q, Rahman SS. The lattice Boltzmann method for isotothermal micro-gaseous flow and its application in shale gas flow: A review. *Int J Heat Mass Transf.* 2016;95:94-108.
11. Yu X, Vayssade B. Joint profiles and their roughness parameters. *Int J Rock Mech Mining Sci Geomech Abst.* 1991:28:333-336.
12. Yuan B, Wang Y, Zeng S. Effect of slick water on permeability of shale gas reservoirs. *J Energy Res Technol.* 2018:140:112901-112907.
13. Zhangan B, Ahmadi M, Hanks C, Awoleke O. The role of hydraulic fracture geometry and conductivity profile, unpropped zone conductivity and fracturing fluid flowback on production performance of shale oil wells. *J Unconvent Oil Gas Res.* 2015:9:103-113.
14. Zhang R-H, Zhang L-H, Tang H-Y, et al. A simulator for production prediction of multistage fractured horizontal well in shale gas reservoir considering complex fracture geometry. *J Nat Gas Sci Eng.* 2019;67:14-29.
15. Zhao T, Zhao H, Li X, et al. Pore scale characteristics of gas flow in shale matrix determined by the regularized lattice Boltzmann method. *Chem Eng Sci.* 2018;187:245-255.
16. Zhao Y-L, Wang Z-M, Qin X, Li J-T, Yang H. Stress-dependent permeability of coal fracture networks: A numerical study with lattice Boltzmann method. *J Petrol Sci Eng.* 2019:173:1053-1064.
17. Zhou L, Shen Z, Wang J, Li H, Lu Y. Numerical investigating the effect of nonuniform proppant distribution and unpropped fractures on well performance in a tight reservoir. *J Petrol Sci Eng.* 2019;177:634-649.
18. Zhou T, Zhang S, Feng Y, Shuai Y, Zou Y, Li N. Experimental study of permeability characteristics for the cemented natural fractures of the shale gas formation. *J Nat Gas Sci Eng.* 2016;29:345-354.
19. Zhu W, Ma D. Effective stress characteristics in shale and its effect on shale gas productivity. *J Nat Gas Geo.* 2018;3:339-346.
20. Zimmerman RW, Kumar S, Bodvarsson GS. Lubrication theory analysis of the permeability of rough-walled fractures. *Int J Rock Mech Mining Sci Geomech Abst.* 2019;177:634-649.
21. Barton N. (1971). A relationship between joint roughness and joint shear strength. *Rock Fracture-Proc, Int. Symp. on Rock Mechanics, Nancy, France, paper 1–8.
22. d’Humieres D, Ginzbarg I, Krafczyk M, Lallemand P, Luo LS. Multiple-relaxation-time lattice Boltzmann models in three dimensions. *Philos Trans R Soc Lond. Ser A: Math Phys Eng Sci.* 2002;360(1792):437-451. https://doi.org/10.1098/rsta.2001.0955

How to cite this article: Lu C, Lu Y, Gou X, Zhong Y, Chen C, Guo J. Influence factors of unpropped fracture conductivity of shale. *Energy Sci Eng.* 2020;8:2024–2043. https://doi.org/10.1002/ese3.645
APPENDIX A

Numerical reconstruction model building process

The data of the upper and lower surfaces of the fracture are obtained via laser scanning. Then, the data are collated, and the original height matrices of the upper and lower surfaces of the fracture are obtained, defined as $A_0$ and $A_1$, respectively.

$$
\begin{align*}
A_0 &= (a_{0ij}), (i = 1,2,3, \ldots, m; j = 1,2,3, \ldots, n) \\
A_1 &= (a_{1ij}), (i = 1,2,3, \ldots, m; j = 1,2,3, \ldots, n)
\end{align*}
$$

(A1)

The numerical reconstruction of misalignment includes the following steps: removal of the substrate, symmetric placement, misalignment movement, and double-wall single-point contact.

Removal of the substrate

First, the substrate is selected as the lowest point of the fracture surface. Then, all the grid data of the fracture surface are subtracted from the height of the lowest point (Figure A1).

$$
\begin{align*}
A_0' &= (a_{0ij}') = [a_{0ij} - \min(a_{0ij})], (i = 1,2,3, \ldots, m; j = 1,2,3, \ldots, n) \\
A_1' &= (a_{1ij}') = [a_{1ij} - \min(a_{1ij})], (i = 1,2,3, \ldots, m; j = 1,2,3, \ldots, n)
\end{align*}
$$

(A2)

Symmetric placement

As the upper fracture surface is in the reverse state when laser scanning is performed, it needs to be vertically reversed to obtain the vertical-reverse height division of the upper fracture surface, $A_{0R}$.

$$
A_{0R} = (a_{0Rij}) = [a_{0ij}' - \max(a_{0ij}')] , (i = 1,2,3, \ldots, m; j = 1,2,3, \ldots, n)
$$

(A3)

The height division of the upper fracture surface is added to the highest value of the lower fracture surface to obtain a plane symmetric placement matrix of the upper fracture surface, and the lower fracture surface remains unchanged, thereby obtaining a double-wall face-symmetric placement map (Figure A3).

$$
\begin{align*}
A_{0S} &= (a_{0Sij}) = [a_{0ij}' + \max(a_{0ij}')] , (i = 1,2,3, \ldots, m; j = 1,2,3, \ldots, n) \\
A_{1S} &= A_1'
\end{align*}
$$

(A4)

Misalignment movement

The misalignment movement is performed by fixing the lower fracture surface and moving the upper fracture surface. Therefore, the misalignment movement of the fracture has three modes: forward movement, horizontal movement, and inclined movement.

Considering the directions of tensile fracture and geostress, the forward movement mode is often used. The misalignment movement steps are as follows:

- The fracture morphology is set to $(\delta/10)$ mm.
- The fracture morphology $\delta$ needs to be added to the matrix ordinate of the upper fracture wall surface, and the matrix abscissa is unchanged.
- The abscissa is maintained constant, and point A is defined in Figure A5 (c) as 0 on the ordinate and point B as the maximum value on the ordinate.

After the misalignment movement is completed, the height divisions of the upper and lower fracture surfaces are obtained as $A_{0SDIS}$ and $A_{1SDIS}$, respectively.

$$
\begin{align*}
A_{0SDIS} &= (a_{0SDISij}) = (a_{0ij} + \delta), (i = 1,2,3, \ldots, m; j = 1,2,3, \ldots, n) \\
A_{1SDIS} &= (a_{1SDISij}) = (a_{1ij} + \delta), (i = 1,2,3, \ldots, m; j = 1,2,3, \ldots, n - \delta)
\end{align*}
$$

(A5)

Double-wall single-point contact

The fracture minimum width $w_{\text{min}}$ after misalignment is subtracted from the mesh data of the fracture upper surface, and the height matrices of the upper and lower fracture surfaces $Z_u$ and $Z_d$, respectively, after the contact are obtained.

$$
\begin{align*}
Z_u &= (z_{ui}) = [a_{\text{0SDISij}} - \min(a_{\text{0SDISij}} - a_{\text{1SDISij}})] , (i = 1,2,3, \ldots, m; j = 1,2,3, \ldots, n - \delta) \\
Z_d &= A_{1SDIS}
\end{align*}
$$

(A6)

The original fracture surface is calculated by A1–A6, and the numerical simulation models (A7) and (A8) of the fracture surface are obtained.

$$
\begin{align*}
A_2 &= (a_{2ij}), (i = 1,2,3, \ldots, m; j = 1,2,3, \ldots, n) \\
A_2' &= (a_{2ij}') = [a_{2ij} - \min(a_{2ij})], (i = 1,2,3, \ldots, m; j = 1,2,3, \ldots, n) \\
A_{4S} &= (a_{4Sij}) = [a_{4ij}' - \max(a_{4ij}')] , (i = 1,2,3, \ldots, m; j = 1,2,3, \ldots, n) \\
A_{4S} &= (a_{4Sij}) = [a_{4ij}' + \max(a_{4ij}')] , (i = 1,2,3, \ldots, m; j = 1,2,3, \ldots, n) \\
A_{4SDIS} &= (a_{4SDISij}) = (a_{4ij} + \delta), (i = 1,2,3, \ldots, m; j = 1,2,3, \ldots, n - \delta) \\
Z_u &= (z_{ui}) = [a_{\text{4SDISij}} - \min(a_{\text{4SDISij}} - a_{\text{1SDISij}})] , (i = 1,2,3, \ldots, m; j = 1,2,3, \ldots, n - \delta)
\end{align*}
$$

(A7)

$$
\begin{align*}
A_1 &= (a_{1ij}), (i = 1,2,3, \ldots, m; j = 1,2,3, \ldots, n) \\
A_1' &= (a_{1ij}') = [a_{1ij} - \min(a_{1ij})], (i = 1,2,3, \ldots, m; j = 1,2,3, \ldots, n) \\
A_{1S} &= A_1' \\
A_{1SDIS} &= (a_{1SDISij}) = (a_{1ij} + \delta), (i = 1,2,3, \ldots, m; j = 1,2,3, \ldots, n - \delta) \\
Z_d &= A_{1SDIS}
\end{align*}
$$

(A8)
**FIGURE A1**  Removal of fracture substrate

**FIGURE A2**  Vertical-reverse operation of upper fracture surface

**FIGURE A3**  Symmetric placement of fracture in double walls

**FIGURE A4**  Misalignment movement forms of unpropped fracture

**FIGURE A5**  Diagram of double-wall fracture misalignment movement
APPENDIX B

Fracture deformation model building process
The process consists of three sets of calculation models: discrete microelement contact compression calculation, discrete microelement deformation calculation under stress, and fracture damage determination.

Discrete microelement contact compression calculation
The microelement height division of the upper fracture surface is $Z_1$, and the microelement height division of the lower fracture surface is $Z_2$.

$$\begin{align*}
Z_1 &= \max(z_{uij} - z_{dij}),(i = 1,2,3, \ldots m; j = 1,2,3, \ldots n - \delta) \\
Z_2 &= Z_d 
\end{align*}$$

(B1)

The lower fracture surface remains unchanged, the upper fracture surface moves downward $z$ under closed stress, and the height division of the upper fracture surface after deformation is obtained as $Z_u'$.

$$Z_u' = (z_{uij}') = (z_{uij} - Z),(i = 1,2,3, \ldots m; j = 1,2,3, \ldots n - \delta)$$

(B2)

Then, the fracture morphology matrix $Z_c$ can be expressed as follows:

$$Z_c = Z_a - Z_u'$$

(B3)

When the element $z_{cj}$ in the fracture morphology matrix ($Z_c$) is greater than 0, it indicates that the microcell has no contact under the fracture morphology $z$. When $z_{cj}$ is less than 0, it indicates that the microelement has undergone contact deformation under the fracture morphology $z$, and the compression is $|z_{cj}|$. $\Delta Z$ is defined as the discrete microelement contact compression matrix, and $\Delta z_{cj}$ represents the elements in this matrix. Then, the discrete microelement contact compression matrix $\Delta Z$ can be expressed as (B4).

$$\Delta Z = (\Delta z_{cj}) = \begin{cases} 0, & z_{cj} \geq 0 \\
|z_{cj}|, & z_{cj} \leq 0 \end{cases} (i = 1,2,3, \ldots m; j = 1,2,3, \ldots n - \delta)$$

(B4)

Discrete microelement deformation calculation under stress
The shale fractures are discretely formed as square elements. One of these discrete units in contact is considered for analysis.

Upper fracture surface microbody deformation
We assume that the fracture surface microelement compression is $\Delta Z_1$, and its strain $\varepsilon_{z1}$ is given by

$$\varepsilon_{z1} = \frac{\Delta Z_1}{Z_1}$$

(B5)

Substituting (B5) into the generalized Hooke’s law, $\varepsilon_{z1} = \frac{1}{E} [\sigma_z - \nu(\sigma_x + \sigma_y)]$, we obtain (B6).

$$\frac{\Delta Z_1}{Z_1} = \frac{1}{E} [\sigma_z - \nu(\sigma_x + \sigma_y)]$$

(B6)

When $\sigma_x = 0$ and $\sigma_y = 0$, then

$$\frac{\Delta Z_1}{Z_1} = \frac{1}{E} \sigma_z$$

(B7)

Assuming that the lateral deformation of the upper fracture surface microbody is $\Delta X_1$, and the force is $\Delta F_z$: the stress $\sigma_z$ of the upper fracture surface microbody in the z-direction is

$$\sigma_z = \frac{\Delta F_z}{\Delta A} = \frac{\Delta F_z}{(X + \Delta X_1)^2}$$

(B8)

Substituting (B8) into (B7), the force deformation (B9) of the upper microelement is obtained.

$$\frac{\Delta Z_1}{Z_1} = \frac{1}{E} \frac{\Delta F_z}{(X + \Delta X_1)^2}$$

(B9)

Lower fracture surface microbody deformation
We assume that the lower fracture surface microelement compression is $\Delta Z_2$, and its lateral deformation is $\Delta X_2$. The force deformation Equation B10 of the upper microelement is obtained as

$$\frac{\Delta Z_2}{Z_2} = \frac{1}{E} \frac{\Delta F_z}{(X + \Delta X_2)^2}$$

(B10)
According to the definition of Poisson's ratio ($\nu$), we have

\[ \nu = \frac{\Delta X_1}{\Delta Z_1} = \frac{\Delta X_2}{\Delta Z_2} \]  

(B11)

The total contact displacement is the sum of the compression amounts of the upper and lower fracture surface microbodies.

\[ \Delta Z_1 + \Delta Z_2 = \Delta Z \]  

(B12)

According to Equation B11, we have

\[ \Delta X_1 = \frac{\nu X \Delta Z_1}{Z_1} \]  

(B13)

\[ \Delta X_2 = \frac{\nu X \Delta Z_2}{Z_2} \]  

(B14)

Substituting (B13) and (B14) into (B8), we obtain

\[ \Delta F_z = \frac{\Delta Z_1 E \left( X + \frac{\nu X \Delta Z_1}{Z_1} \right)^2}{Z_1} \]  

(B15)

\[ \Delta F_z = \frac{\Delta Z_2 E \left( X + \frac{\nu X \Delta Z_2}{Z_2} \right)^2}{Z_2} \]  

(B16)

Solving the simultaneous Equations B13, B14, and B12, we obtain

\[ \Delta Z_1 \left( \frac{\nu^2}{Z_1^3} + \frac{\nu^2}{Z_2^3} \right) + \Delta Z_2 \left( \frac{2Z_1 \nu^2}{Z_1^3} + \frac{3\Delta Z_1 \nu^2}{Z_1^3} + \frac{2Z_2 \nu^2}{Z_2^3} \right) + \Delta Z_1 \left( \frac{1}{Z_1^3} + \frac{Z_1^3 + 4\nu \Delta ZZ_2 + 3\Delta Z_1^3}{Z_2^3} \right) - \frac{Z_2^3 \Delta Z + 2Z_2 \nu \Delta Z^2 + \nu \Delta Z^3}{Z_2^3} = 0 \]  

(B17)

Considering fracture damage determination

When the shale only undergoes linear elastic deformation, the closed stress is

\[ \sigma_0 = \frac{\Delta F_z}{(X + \Delta X_1)^2} \]  

(B18)

Substituting Equations B13 into B18, we obtain Equation B19.

\[ \sigma_0 = \frac{\Delta F_z Z_1^2}{X^2(Z_1 + \nu \Delta Z_1)^2} \]  

(B19)

When $\sigma_0$ is greater than the compressive strength of shale $\sigma_m$, the shale undergoes stress damage. When $\sigma_0 \leq \sigma_m$, the closed stress is $\sigma_0$.

The stress of the shale fracture during contact deformation is as follows:

\[ \sigma = \begin{cases} 
\sigma_0, & \sigma_0 \leq \sigma_m \\
\sigma_m M_\epsilon, & \sigma_0 \geq \sigma_m
\end{cases} \]  

(B20)

The stress $\sigma$ and displacement $Z$ calculation model $\sigma = f(Z)$ for the stress-damaged fracture is as follows:

\[ Z_1 = \max \left( z_{uij} - z_{uij} \right), \quad (i = 1, 2, 3, \ldots, m; j = 1, 2, 3, \ldots, n - \delta) \]

\[ Z_2 = Z_0 \]

\[ Z'_0 = (z'_{uij} - Z), \quad (i = 1, 2, 3, \ldots, m; j = 1, 2, 3, \ldots, n - \delta) \]

\[ Z_c = Z_0 - Z'_0 \]  

(B21)

\[ \Delta Z = (\Delta z_{uij}) = \begin{cases} 
0, & z_{uij} \geq 0 \\
z_{uij}, & z_{uij} < 0
\end{cases} \]  

(B22)
The fracture width distribution $W_f$ under closed stress is given by

$$W_f = \begin{cases} \Delta z_{ij}^3 \left( \frac{v^2}{z_{ij}^3} + \frac{v^3}{z_{ij}^4} \right) + \Delta z_{ij}^2 \left( \frac{2z_{1j}v^3}{z_{ij}^3} + \frac{33z_{ij}v^2 + 2z_{2j}v}{z_{ij}^3} \right) + \Delta z_{1ij} \left( \frac{1}{z_{1ij}^3} + \frac{z_{2j}^2 + 4v \Delta z_{ij}z_{2j}^2 + 3 \Delta z_{ij}^2 v^2}{z_{ij}^3} \right), \\ \Delta z_{ij}^2 \Delta z_{ij} + 2z_{2j}v \Delta z_{ij}^2 + v \Delta z_{ij}^3 \\ \end{cases} = 0$$

(B23)

\[
\sigma = \sum_{i=1}^{m} \sum_{j=1}^{n-\delta} \begin{cases} \Delta z_{ij}^3 \left( \frac{v^2}{z_{ij}^3} + \frac{v^3}{z_{ij}^4} \right) + \Delta z_{ij}^2 \left( \frac{2z_{1j}v^3}{z_{ij}^3} + \frac{33z_{ij}v^2 + 2z_{2j}v}{z_{ij}^3} \right) + \Delta z_{1ij} \left( \frac{1}{z_{1ij}^3} + \frac{z_{2j}^2 + 4v \Delta z_{ij}z_{2j}^2 + 3 \Delta z_{ij}^2 v^2}{z_{ij}^3} \right), \\ \Delta f_{ij} = \frac{\Delta z_{ij}E}{z_{1ij}^2} \left( X + \frac{vX \Delta z_{ij}}{z_{ij}} \right)^2 \\ \sigma_{0ij} = \frac{\Delta F_{ij}z_{ij}^2}{X^2(z_{1ij} + v \Delta z_{1ij})^2} \\ \sigma_{ij} = \begin{cases} \sigma_{0ij}, \sigma_0 \leq \sigma_m, \\ \sigma_m, \sigma_0 \geq \sigma_m \\ \end{cases} \\ \end{cases} \]

The fracture width distribution $W_f$ under closed stress is given by

$$W_f = (w_{fij}) = \begin{cases} \Delta z_{ij} \geq 0, \\ 0, \Delta z_{ij} \leq 0 \end{cases} \tag{B24}$$

**APPENDIX C**

**Boundary determination of 3D LBM model**

Determining whether the computational particles in the grid are at the boundary or in the flow channel is the key to the 3D LBM model. In this study, “0 1 flag” is used to determine the boundary of the fracture space structure. “0” and “1” represent the flow channel and solid, respectively (Figure C1).

In this study, the periodic flow boundary of the fluid driven by gravity is applied. The solid-liquid boundary at the inlet and outlet must be the same. Therefore, the fluid buffers at the inlet and outlet were built during calculation.

**FIGURE C1** Schematic diagram of “0 1 flag” marking the boundary of fracture space structure

**FIGURE C2** Inlet and outlet buffers of fluids
**APPENDIX D**

**Conductivity calculation results for orthogonal analysis**

The conductivity of five rock samples was calculated using the established unpropped fracture conductivity model of shale. The results are presented in Table D1. Some actual core samples after the experiment are shown in Figure D1.

**TABLE D1** Orthogonal calculation results of the influencing factors of the unpropped fracture conductivity of shale

| Roughness | Misalignment (mm) | Closed stress (MPa) | Young's modulus (GPa) | Poisson's ratio | Compressive strength (MPa) | Conductivity ($\mu$m²·cm) |
|-----------|-------------------|---------------------|-----------------------|-----------------|--------------------------|--------------------------|
| 2.467 (1#) | 3                 | 2                   | 35                    | 0.23            | 300                      | 236.82                   |
| 2.879 (3#) | 3                 | 30                  | 20                    | 0.29            | 400                      | 68.34                    |
| 2.467 (1#) | 1                 | 1                   | 20                    | 0.20            | 200                      | 138.46                   |
| 2.639 (4#) | 5                 | 30                  | 40                    | 0.20            | 300                      | 73.39                    |
| 2.467 (1#) | 4                 | 30                  | 30                    | 0.32            | 350                      | 23.81                    |
| 2.861 (5#) | 3                 | 3                   | 30                    | 0.20            | 250                      | 547.09                   |
| 2.879 (3#) | 4                 | 3                   | 40                    | 0.23            | 200                      | 651.74                   |
| 2.861 (5#) | 1                 | 2                   | 40                    | 0.32            | 400                      | 397.11                   |
| 2.639 (4#) | 3                 | 4                   | 25                    | 0.32            | 200                      | 272.13                   |
| 2.726 (2#) | 5                 | 2                   | 30                    | 0.29            | 200                      | 579.82                   |
| 2.726 (2#) | 3                 | 1                   | 40                    | 0.26            | 350                      | 1387.16                  |
| 2.467 (1#) | 5                 | 3                   | 25                    | 0.26            | 400                      | 246.37                   |
| 2.861 (5#) | 5                 | 4                   | 20                    | 0.23            | 350                      | 741.96                   |
| 2.879 (3#) | 5                 | 1                   | 35                    | 0.32            | 250                      | 1096.46                  |
| 2.879 (3#) | 2                 | 2                   | 25                    | 0.20            | 350                      | 623.10                   |
| 2.861 (5#) | 2                 | 30                  | 35                    | 0.26            | 200                      | 41.34                    |
| 2.639 (4#) | 2                 | 1                   | 30                    | 0.23            | 400                      | 594.38                   |
| 2.879 (3#) | 1                 | 4                   | 30                    | 0.26            | 300                      | 325.43                   |
| 2.726 (2#) | 4                 | 4                   | 35                    | 0.20            | 400                      | 429.92                   |
| 2.467 (1#) | 2                 | 4                   | 40                    | 0.29            | 250                      | 219.89                   |
| 2.861 (5#) | 4                 | 1                   | 25                    | 0.29            | 300                      | 1128.62                  |
| 2.726 (2#) | 2                 | 3                   | 20                    | 0.32            | 300                      | 473.29                   |
| 2.726 (2#) | 1                 | 30                  | 25                    | 0.23            | 250                      | 30.52                    |
| 2.639 (4#) | 1                 | 3                   | 35                    | 0.29            | 350                      | 76.92                    |
| 2.639 (4#) | 4                 | 2                   | 20                    | 0.26            | 250                      | 583.10                   |
FIGURE D1  Actual core samples after the experiment