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Large-Scale Experimental Study of Proppant Transport and Placement in Rough Fractures of Conglomerate Reservoirs

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Abstract

Proppant placement in rough fractures is controlled by coupled effects of operating parameters, particle settling, and fracture-surface heterogeneity, yet quantitative criteria for evaluating final placement remain limited. This study reanalyzes previously obtained large-scale visualization data from a 20.3 m × 4.5 m × 10 mm rough-fracture system and develops an engineering-oriented framework for quantitative placement evaluation. Five indicators were introduced: normalized effective supported area, normalized effective supported length, near-wellbore accumulation ratio, distal coverage ratio, and ridge-height coefficient of variation. Their responses to pumping rate, fracturing-fluid viscosity, proppant size, and sand concentration were systematically compared.

Results show that pumping rate primarily controls distal transport. Increasing the model pumping rate from 0.12 to 0.24 m³/min increased the normalized supported length from 0.875 to 1.000 and the distal coverage ratio from 0.026 to 0.115. Fluid viscosity and sand concentration showed stronger local sensitivities with respect to overall supported area, whereas particle size mainly affected the balance between distal transport and local deposition. Based on the combined indicators, four representative placement patterns were identified: near-wellbore accumulation, uniform spreading, distal-deficient placement, and bridging-prone high-loading placement.

An exploratory four-factor power-law correlation was further evaluated using leave-one-out cross-validation. Although the in-sample fit was moderate, the LOOCV results showed limited predictive robustness, indicating that the correlation should be treated as a geometry-specific summary rather than a validated predictive model. The proposed indicators and classification framework provide a quantitative basis for comparing proppant-placement quality in large-scale rough fractures.

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Keywords

Rough fracture; Proppant transport; Proppant placement; Effective supported area; Placement classification; Large-scale physical simulation.

1. Introduction

For conglomerate reservoirs, the effectiveness of hydraulic fracturing depends not only on fracture creation but also on whether proppants can form a continuous and mechanically stable supported pathway after entering highly irregular fractures. In field practice, treatment designs usually specify pump rate, fluid viscosity, particle size, and sand concentration separately; however, the final placement result is controlled by their coupled effect. Therefore, a key challenge is to convert laboratory observations of proppant migration into engineering indicators that can be used

for parameter selection and risk prediction. Among these, deep conglomerate reservoirs, such as those in the Mahu oilfield, exhibit significant heterogeneity, high gravel content, and irregular cementation patterns, which generate fractures with highly rough surfaces and multiscale mechanical discontinuities. These geological features pose major challenges for proppant transport and placement, as irregular fracture geometries promote local flow stagnation, premature near-wellbore deposition, and insufficient distal support (Huang et al., 2020; Huang et al., 2019; Sahai & Moghanloo, 2019; Zhang et al., 2020).

Early experimental studies of proppant transport primarily utilized smooth parallel-plate or short slot-flow models, enabling observation of basic sedimentation and dune formation patterns. These small-scale experiments provided initial insights into the influence of fluid viscosity, injection rate, and particle size on proppant transport. (Isah et al., 2021; Li et al., 2021). However, such idealized models cannot replicate the flow heterogeneity and multi-scale roughness inherent in deep conglomerate fractures, limiting their applicability for predicting field-scale proppant distribution.

To address this limitation, researchers progressively introduced rough-wall surfaces, inclined fracture planes, and branched geometries into laboratory setups. Fernández et al. (2019) and Ma et al. (2022) demonstrated that protruding clasts and local obstacles induce complex flow recirculation and turbulence, which significantly affect the suspension and transport of proppant. (Fernández et al., 2019; Ma et al., 2022). Isah et al. (2021) highlighted that these geometric features strongly influence both near-wellbore accumulation and distal coverage, emphasizing the necessity of incorporating fracture roughness into experimental designs (Isah et al., 2021).

Despite these advances, most existing studies are constrained by limited fracture length (< 6 m) or simplified boundary conditions, restricting the ability to capture long-distance transport and layered deposition phenomena observed in field operations (Novotny, 1977; Zhao et al., 2021). Numerical studies using CFD–DEM coupling have enhanced understanding of multi-particle interactions in complex fractures, but require experimental validation to ensure physical realism (Cipolla et al., 2008; Sahai et al., 2014). Moreover, scaling laboratory findings to field applications remains challenging due to differences in fracture height, width, and fluid dynamics.

Recent efforts have demonstrated the value of large-scale experimental platforms, ranging from laboratory tanks simulating multi-branch fractures to large-scale rigs capable of replicating fractures tens of meters long (Lv et al., 2022). These systems enable the study of long-range proppant transport, layered sand ridge formation, and the influence of fluid viscosity, particle size, and injection rate under controlled conditions while retaining key geometric features of field fractures. They provide critical insights into the mechanistic processes governing proppant transport in deep, heterogeneous reservoirs, which cannot be captured by small-scale or idealized models alone.

The large-scale experimental system and the raw data on proppant transport used in this study were previously published by a team that included the authors of this paper (Xie et al., 2026). The present study does not report a new experimental campaign. Instead, the existing visualization images, operating records, pressure data, and final proppant-placement profiles are reanalyzed from an engineering-evaluation perspective. Specifically, the objectives of this study are to: (1) establish measurable indicators for effective supported area, supported length, near-wellbore accumulation, distal coverage, and placement uniformity; (2) quantify the local normalized sensitivities of pumping rate, fluid viscosity, proppant size, and sand concentration; (3) develop quantitative criteria for distinguishing typical placement patterns; and (4) establish and internally evaluate a geometry-specific empirical relationship for proppant-placement prediction. The applicability and limitations of the proposed framework are also discussed.

2. Materials and Methods

2.1. Experimental Materials and Equipment

The experimental database used in this work was obtained from a large visual fracture model designed for rough conglomerate-fracture conditions. The model provides a 20.3 m proppant-transport path and a 4.5 m vertical observation window (**Figure 1**), which makes it possible to capture the long-distance development of sand ridges under controlled hydraulic conditions. Polymer-based slickwater fracturing fluids with different viscosity levels were used as carrying fluids, and quartz-sand proppants with particle-size ranges of 20/40, 40/70, and 70/140 mesh were

selected to represent typical field proppant systems. The experimental variables included pump rate, fluid viscosity, proppant size, and sand concentration. Different from studies focusing on apparatus development or direct phenomenological description, this paper uses the recorded visualization images, pressure data, and final sand-ridge profiles as an experimental database for further quantitative analysis. Based on these data, normalized indicators are constructed to evaluate effective supported area, distal transport capacity, and sand-ridge stability in rough fractures.

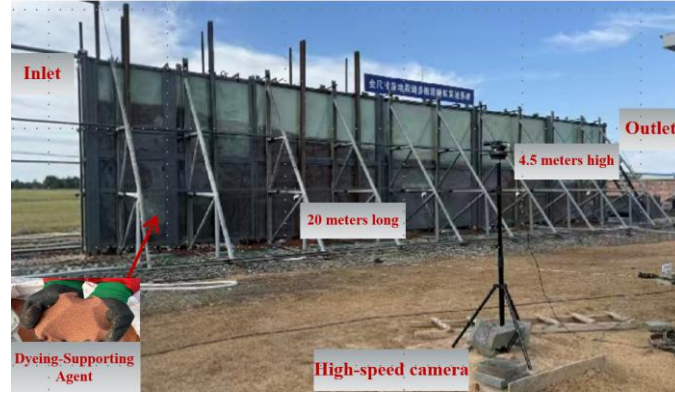


Figure 1. Full-Scale Multiphase Flow Deep-Ground Simulation Experimental System.

2.2. Rough-Textured Wall Design

The rough fracture surface was treated as a fixed geometric boundary condition in the present study rather than being described only qualitatively. Surface-elevation data obtained from the reconstructed fracture were used to characterize both the amplitude and spatial variation of the surface morphology. The arithmetic mean roughness R_a was adopted as the primary amplitude-related descriptor, while representative profiles extracted along the flow and vertical directions were used to illustrate the spatial fluctuations of the fracture surface. These geometric characteristics provide a quantitative basis for interpreting the spatially nonuniform proppant-deposition patterns observed in the subsequent experiments.

The artificial fracture surface was reconstructed from high-resolution topographical data obtained from a representative conglomerate-reservoir fracture surface. As shown in **Figure 2a**, the reconstructed surface exhibits pronounced asperities, depressions, and undulating features distributed in both the longitudinal (X) and vertical (Y) directions. The local surface-elevation variation is approximately 15–80 mm, indicating substantial geometric heterogeneity over the investigated area. Such multiscale topographical variations reproduce the principal geometric characteristics of rough conglomerate fractures and provide potential sites for local flow disturbance and particle retention.

To quantify the surface morphology, representative profiles were extracted along the X and Y directions, as shown in **Figure 2b** and **Figure 2c**. The profiles exhibit irregular peaks, valleys, and local protrusions, demonstrating the pronounced spatial variability of the reconstructed fracture surface. The arithmetic mean roughness was calculated as

$$R_a = \frac{1}{N} \sum_{i=1}^N |z_i - \bar{z}| \quad (1)$$

where z_i is the local surface elevation, $\bar{z}$ is the mean elevation of the selected profile, and N is the number of sampled points. The resulting characteristic roughness was approximately $R_a = 14$ mm. This value, together with the observed elevation range and profile undulation, indicates that the reconstructed surface retains pronounced roughness characteristics representative of the fracture morphology considered in this study. The preferential deposition observed near asperities and depressions is therefore interpreted as being associated with local geometric disturbances and potential low-velocity or particle-trapping regions, rather than as direct evidence of a measured local flow field.

The digitized fracture morphology was first converted into a three-dimensional mold, which was fabricated using 3D printing. The printed mold was subsequently used for casting an artificial rock-like material to reproduce the rough fracture surface in the large-scale physical model. This fabrication procedure preserved the principal asperities, depressions, and multiscale geometric fluctuations of the digitized surface while providing the mechanical integrity required for large-scale proppant-transport experiments. The same reconstructed fracture geometry and roughness

realization were used for all ten operating cases. Therefore, surface roughness was treated as a fixed geometric condition in the present analysis rather than as an independently varied experimental factor. Consequently, the results and empirical relationships developed in this study are applicable primarily to rough-fracture geometries similar to that investigated and should not be interpreted as universal relationships describing the independent effect of fracture roughness.

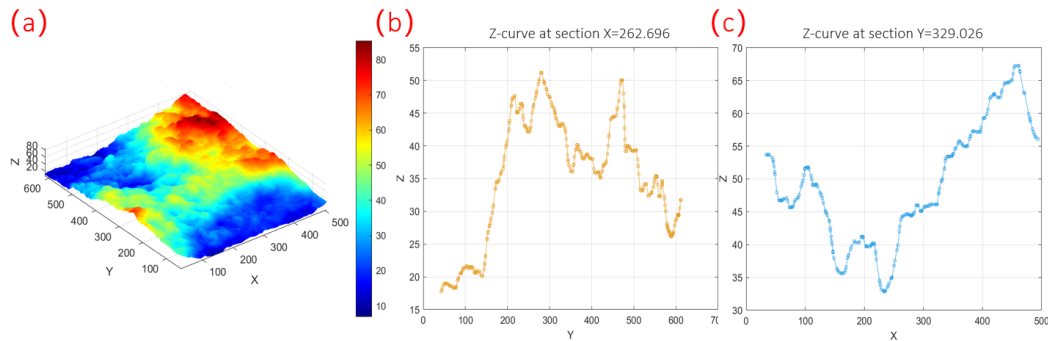


Figure 2. Rough-textured wall design. (a) 3D scan of the surface of a fissure in conglomerate rock, showing a surface elevation map; (b) Height profile in the X direction; (c) Height profile in the Y direction.

2.3. Experimental Protocol Design

To establish the correspondence between the large-scale physical model and field-scale fracture conditions, Froude similarity was adopted as the primary dynamic-similarity criterion, while the Reynolds number was used as an auxiliary parameter for evaluating flow-regime consistency. The Froude number characterizes the relative importance of flow inertia and gravitational effects and is therefore particularly relevant to proppant transport, where forward migration competes with gravitational settling. In contrast, the Reynolds number reflects the balance between inertial and viscous forces and was used to assess whether the model and field conditions remained within comparable flow regimes rather than as a strictly matched similarity criterion (Liu et al., 2022).

The experimental fracture had dimensions of 20.3 m in length, 4.5 m in height, and 10 mm in aperture. The representative field fracture aperture was also taken as 10 mm, giving an aperture scale ratio of unity. The field-to-model pumping-rate ratio was fixed at 25, corresponding to 3–6 m³/min under field conditions and 0.12–0.24 m³/min in the physical model. Assuming identical scaling in the fracture-length and fracture-height directions, Froude similarity yields an in-plane geometric scale ratio of approximately 8.55 and a field-to-model mean-velocity ratio of approximately 2.924. Accordingly, the 20.3 m × 4.5 m × 10 mm experimental fracture represents a field-scale fracture of approximately 171.0 m × 38.47 m × 10 mm. The resulting geometric and dynamic scaling relationships are summarized in **Table 1**.

Because the fracture aperture and fluid properties were maintained at the same values in the field and model conditions, exact Reynolds-number similarity cannot be satisfied simultaneously with the adopted Froude scaling. The hydraulic diameters of the field and model fractures are nearly identical (approximately 19.995 and 19.956 mm, respectively), whereas the field-to-model mean-velocity ratio is approximately 2.924. Consequently, the Reynolds-number ratio is approximately 2.93. Therefore, Reynolds-number similarity was used only as an auxiliary consistency check, whereas Froude-number similarity governed the field-to-model scaling. Based on this scaling relationship, the effects of pumping rate, fracturing-fluid viscosity, proppant size, and sand concentration were evaluated using the ten operating cases listed in **Table 2**.

Table 1. Geometric and dynamic scaling relationship.

Parameter	Field	Model	Scale (n/m)
Fracture length	171.0 m	20.3 m	8.55
Fracture height	38.47 m	4.5 m	8.55
Fracture aperture	10 mm	10 mm	1
Flow rate	3–6 m ³ /min	0.12–0.24 m ³ /min	25
Mean velocity	—	—	2.924
Froude number	—	—	1
Hydraulic diameter	≈19.995 mm	≈19.956 mm	≈1.002
Reynolds number	—	—	≈2.93

Table 2. Field-to-model parameter conversion and experimental cases used for placement evaluation.

Cases	On-site single-cluster pump discharge volume (m ³ /min)	Experimental pump discharge volume (m ³ /min)	Viscosity mPa·s	Proppant particle size (mesh)	Sand concentration (kg/m ³)
1	4	0.16	10(Low)	40/70	100
2	4	0.16	10(Low)	40/70	200
3	4	0.16	10(Low)	40/70	300
4	3	0.12	20(Medium)	40/70	100
5	4	0.16	20(Medium)	20/40	100
6	4	0.16	20(Medium)	40/70	100
7	4	0.16	20(Medium)	70/140	100
8	4	0.16	40(High)	40/70	100
9	5	0.20	20(Medium)	40/70	100
10	6	0.24	20(Medium)	40/70	100

2.4. Definition of Quantitative Placement Indicators

To convert the final proppant-ridge morphology into reproducible engineering descriptors, the final deposited-proppant profiles obtained from the visualization experiments were digitized along the fracture length (**Table 3**). The extracted ridge-height profile is denoted by $h(x)$, where x represents the distance from the fracture inlet and $h(x)$ represents the local proppant-ridge height. All profiles were mapped onto a common spatial coordinate system along the 20.3 m fracture. Five quantitative indicators were introduced to characterize the final placement quality: normalized effective supported area, normalized effective supported length, near-wellbore accumulation ratio, distal coverage ratio, and the coefficient of variation of proppant-ridge height.

The normalized effective supported area, referring to the projected supported area in the two-dimensional observation plane, was defined as

$$A_{\text{eff}}^* = \frac{\int_0^{L_f} h(x) dx}{L_f H_f} \quad (2)$$

where L_f and H_f are the fracture length and height, respectively. In the present experiments, $L_f = 20.3$ m and $H_f = 4.5$ m. A larger A_{eff}^* indicates a greater overall filling degree of the fracture.

To characterize the distal extent of effective proppant placement, a minimum reliable ridge-height threshold $h_{\min}$ was introduced according to the spatial resolution and boundary-detection accuracy of the visualization images. The effective supported length and its normalized form were calculated as

$$L_{\text{eff}} = \max\{x | h(x) \geq h_{\min}\} \quad (3)$$

$$L_{\text{eff}}^* = \frac{L_{\text{eff}}}{L_f} \quad (4)$$

where a larger L_{eff}^* represents more effective distal transport.

The first 20% of the fracture length was defined as the near-wellbore evaluation zone. The near-wellbore accumulation ratio was calculated as

$$N_{\text{acc}} = \frac{\int_0^{0.2L_f} h(x) dx}{\int_0^{L_f} h(x) dx} \quad (5)$$

A larger N_{acc} indicates stronger inlet-side accumulation. Similarly, the final 20% of the fracture length was defined as the distal evaluation zone, and the distal coverage ratio was calculated as

$$D_{\text{cov}} = \frac{\int_{0.8L_f}^{L_f} h(x) dx}{\int_0^{L_f} h(x) dx} \quad (6)$$

A larger D_{cov} indicates more effective distal filling. In particular, a relatively large L_{eff}^* combined with a small D_{cov} indicates that proppant reaches the distal region but forms only limited deposition there.

Finally, the geometric uniformity of the deposited proppant was evaluated using the coefficient of variation of the ridge height,

$$CV_h = \frac{S_h}{\bar{h}} \quad (7)$$

where $\bar{h}$ and S_h are the mean and standard deviation of ridge-height values satisfying $h(x) \geq h_{\min}$, respectively. A smaller CV_h indicates a more uniform deposited-proppant profile. Zero-height points outside the effectively supported region were excluded from the calculation so that distal transport deficiency and within-supported-region nonuniformity could be evaluated independently.

Together, A_{eff}^* , L_{eff}^* , N_{acc} , D_{cov} , and CV_h characterize the overall filling degree, transport extent, near-wellbore accumulation, distal filling effectiveness, and placement uniformity, respectively. These indicators were subsequently used for normalized local-sensitivity analysis and quantitative classification of the proppant-placement patterns.

Table 3. Definition and engineering interpretation of quantitative proppant-placement indicators.

Indicator	Symbol	Definition	Engineering interpretation
Normalized effective supported area	A_{eff}^*	$\int h(x)dx/(L_f H_f)$	Overall fracture filling
Normalized effective supported length	L_{eff}^*	L_{eff}/L_f	Distal transport extent
Near-wellbore accumulation ratio	N_{acc}	$A_{0-0.2L}/A_{total}$	Inlet-side accumulation
Distal coverage ratio	D_{cov}	$A_{0.8L-L}/A_{total}$	Distal filling effectiveness
Ridge-height coefficient of variation	CV_h	$s_h/\bar{h}$	Placement uniformity

2.5. Measurement and Data-Processing Uncertainty

Because of the large physical scale, fluid volume, and material consumption of the 20.3 m × 4.5 m fracture system, each operating condition in the present dataset represents one large-scale experimental realization. Independent repeated experiments were not available for all ten operating cases. Therefore, between-test repeatability, replicate-based standard deviations, and confidence intervals are not reported. Instead, the reliability of the quantitative placement indicators was evaluated by considering uncertainties associated with operating-condition measurements, temporal fluctuations during stable pumping, image calibration, and extraction of the final proppant-ridge boundary (Table 4).

Pumping rate and pressure were continuously recorded during each experiment, and representative values were calculated from the stable pumping period. For a measured variable X, the stable-period mean, standard deviation, and coefficient of variation were calculated as

$$\bar{X} = \frac{1}{n} \sum_{i=1}^n X_i \quad (8)$$

$$s_X = \sqrt{\frac{\sum_{i=1}^n (X_i - \bar{X})^2}{n-1}} \quad (9)$$

$$CV_X = \frac{s_X}{\bar{X}} \times 100\% \quad (10)$$

where X_i is the i -th measurement during the stable interval and n is the number of sampled data points. These quantities characterize within-test operating stability and should not be interpreted as between-test repeatability. The stated accuracies of the flow-rate measurement system, pressure sensors, viscosity measurements, and material-weighing devices were also included in the uncertainty assessment.

The quantitative placement indicators defined in Section 2.4 were derived from visualization images and were therefore additionally affected by spatial calibration and boundary-extraction uncertainty. Using the known fracture length L_f and height H_f , the horizontal and vertical spatial calibration factors were determined as

$$k_x = \frac{L_f}{N_x}, k_h = \frac{H_f}{N_h} \quad (11)$$

where N_x and N_h are the corresponding image dimensions in pixels. If the uncertainty in identifying the proppant-ridge boundary is δ_p pixels, the associated dimensional uncertainties are

$$\mu_h = \delta_p k_h, \mu_x = \delta_p k_x \quad (12)$$

To evaluate the propagation of boundary-identification uncertainty to the placement indicators, upper and lower ridge profiles were constructed as

$$h^+(x) = h(x) + \mu_h \quad (13)$$

$$h^-(x) = \max[h(x) - \mu_h, 0] \quad (14)$$

and the normalized effective supported area, effective supported length, near-wellbore accumulation ratio, distal coverage ratio, and ridge-height coefficient of variation were recalculated using the perturbed profiles. For an indicator Y , the corresponding image-processing uncertainty was estimated as

$$\mu_Y = \frac{Y_{\max} - Y_{\min}}{2} \quad (15)$$

where $Y_{\max}$ and $Y_{\min}$ represent the upper and lower values obtained from the boundary-perturbation analysis. Because the effective supported length additionally depends on the minimum reliable ridge-height threshold $h_{\min}$, the sensitivity of L_{eff} to reasonable variations in $h_{\min}$ within the image-resolution range was also examined.

The uncertainty intervals reported in the subsequent analysis therefore represent measurement and data-processing uncertainty rather than confidence intervals obtained from independently repeated experiments. Differences between operating cases that were comparable to the estimated uncertainty range were interpreted as apparent tendencies rather than statistically significant differences.

Table 4. Sources and treatment of measurement and data-processing uncertainty.

Quantity	Primary uncertainty source	Evaluation method	Reported form
Pumping rate	Sensor accuracy and stable-period fluctuation	Instrument specification + temporal statistics	Mean and CV
Pressure	Sensor accuracy and pressure fluctuation	Instrument specification + temporal statistics	Mean and CV
Fluid viscosity	Viscometer accuracy	Instrument specification	Measurement uncertainty
Sand concentration	Mass and fluid-volume measurement	Instrument accuracy/error propagation	Preparation uncertainty
Ridge height ($h(x)$)	Image resolution and boundary extraction	Pixel calibration + boundary perturbation	μ_h
A_{eff}^*	Ridge-boundary uncertainty	Recalculation using perturbed profiles	μ_A
L_{eff}^*	Front location and $h_{\min}$	Boundary/threshold sensitivity	μ_L
N_{acc}	Ridge-boundary uncertainty	Perturbed-profile recalculation	μ_N
D_{cov}	Ridge-boundary uncertainty	Perturbed-profile recalculation	μ_D
CV_h	Ridge-height extraction	Perturbed-profile recalculation	μ_{CV}

2.6. Normalized Local Sensitivity Analysis

To quantitatively compare the relative responses of proppant placement to different operating parameters, a dimensionless local-sensitivity method was adopted. Because pumping rate, fluid viscosity, proppant size, and sand concentration have different physical dimensions and variation ranges, direct comparison of the absolute slopes of the response curves would introduce scale and unit dependence. Therefore, the sensitivity analysis was performed using logarithmic relative changes in the input parameters and placement indicators.

The normalized effective supported area, A_{eff}^* , and normalized effective supported length, L_{eff}^* , defined in Section 2.4 were selected as the primary response variables. A_{eff}^* characterizes the overall filling degree of the fracture, whereas L_{eff}^* characterizes the distal extension of effective proppant placement. The near-wellbore accumulation ratio, distal

coverage ratio, and ridge-height coefficient of variation were used mainly for placement-pattern classification and supplementary interpretation.

For a given operating parameter X_i , the local logarithmic sensitivity between two adjacent operating levels j and $j+1$ was defined as

$$E_{i,j}^{(Y)} = \frac{\ln(Y_{i,j+1}/Y_{i,j})}{\ln(X_{i,j+1}/X_{i,j})} \quad (16)$$

where Y represents either A_{eff}^* or L_{eff}^* , X_i represents the i -th operating parameter, and $E_{i,j}^{(Y)}$ represents the dimensionless local elasticity of response Y to parameter X_i . A positive value indicates that the response increases as X_i increases, whereas a negative value represents an inverse local response.

Because some operating parameters may produce non-monotonic placement responses, particularly fluid viscosity and sand concentration, positive and negative local changes may cancel if their algebraic values are averaged directly. Therefore, the overall local sensitivity magnitude of parameter X_i was calculated using the accumulated absolute logarithmic response:

$$S_i^{(Y)} = \frac{\sum_{j=1}^{m_i-1} \left| \ln\left(\frac{Y_{i,j+1}}{Y_{i,j}}\right) \right|}{\sum_{j=1}^{m_i-1} \left| \ln\left(\frac{X_{i,j+1}}{X_{i,j}}\right) \right|} \quad (17)$$

where m_i is the number of tested levels for parameter X_i . Equation (17) represents the magnitude of the placement response per unit logarithmic variation of the corresponding operating parameter and is therefore dimensionless. The use of absolute values allows the magnitude of non-monotonic responses to be retained without cancellation between increasing and decreasing intervals.

To facilitate comparison among the four operating parameters, the local sensitivities were further normalized as

$$W_i^{(Y)} = \frac{S_i^{(Y)}}{\sum_{k=1}^4 S_k^{(Y)}} \times 100\% \quad (18)$$

where $W_i^{(Y)}$ is the normalized local-sensitivity weight of the i -th parameter with respect to response Y . The four normalized weights sum to 100% by definition. These percentages represent the relative response magnitude within the parameter ranges and operating conditions investigated in the present dataset and should not be interpreted as universal physical contribution ratios or as a statistical decomposition of variance.

The pumping-rate sensitivity was evaluated using Cases 4, 6, 9, and 10; the fluid-viscosity sensitivity was evaluated using Cases 1, 6, and 8; the proppant-size sensitivity was evaluated using Cases 5, 6, and 7; and the sand-concentration sensitivity was evaluated using Cases 1, 2, and 3. Within each group, only the target parameter was varied while the other operating parameters were maintained at the corresponding local reference condition. Because the four parameter groups were not all evaluated around an identical global reference condition, the resulting $W_i^{(Y)}$ values are referred to as normalized local sensitivities rather than global parameter contributions. The experimental groupings are consistent with the ten operating cases listed in the experimental matrix.

For proppant size, the mesh designation was not directly used as a numerical variable in the sensitivity calculation because mesh number is inversely related to physical particle diameter. Instead, each proppant-size class was represented by its characteristic particle diameter, d_p , preferably the measured median particle diameter D_{50} . Thus, the four sensitivity variables were expressed as pumping rate Q , fluid viscosity μ , characteristic proppant diameter d_p , and sand concentration C_m .

The measurement and image-processing uncertainties determined in Section 2.5 were additionally considered when interpreting the sensitivity results. Sensitivity calculations were repeated using the upper and lower bounds of the corresponding placement indicators obtained from the boundary-perturbation analysis. The resulting variation was used to evaluate the robustness of the normalized local-sensitivity ranking. These ranges represent propagated

measurement and data-processing uncertainty rather than confidence intervals derived from independent experimental repetitions.

3. Results

3.1. Proppant-Placement Characteristics in the Rough Fracture

In rough conglomerate fractures, proppant transport and placement are governed by interactions among fracture-surface geometry, local flow redistribution, and particle–wall and particle–particle interactions. Irregular wall morphology creates spatially nonuniform flow and promotes both preferential deposition and bypass zones. Consequently, the final proppant distribution is heterogeneous rather than forming a continuous layer, which can reduce the continuity of the supported flow pathway.



Figure 3. Fluid and particle characteristics within fractures. (a) Schematic illustrating changes in flow regime through the gravel zone; (b) Non-uniform distribution of proppants; (c) Aggregation of proppants in the upper gravel section.

As illustrated in **Figure 3a**, asperities and gravel protrusions deflect the main flow and can generate local recirculation or low-velocity regions. Preferential deposition around these features is consistent with particle trapping in locally reduced-velocity zones, whereas particles in more open, higher-velocity channels remain suspended over longer distances. The resulting contrast produces alternating accumulation and low-coverage regions along the fracture.

At the particle scale, rough walls impose geometric constraints and increase particle–wall and particle–particle collisions. Particles may be trapped in depressions as their kinetic energy decreases, whereas particles passing over protrusions can be re-entrained by local shear and continue downstream. With continued injection, these differences amplify spatially, producing a patchy deposition pattern and pronounced local variations in deposited thickness.

The final placement morphology therefore shows localized clusters and gaps, as illustrated in **Figure 3b** and **Figure 3c**. Regions with stronger carrying capacity remain comparatively clear, whereas reduced-velocity zones promote particle accumulation and the development of multiple local ridges. This discontinuous packing pattern is consistent with the observed multippeak sand-ridge morphology and reduced continuity of the supported pathway.

At the fracture scale, roughness modifies the effective flow channels and introduces additional local energy dissipation. Progressive deposition can further constrict the available flow area, reinforcing flow redistribution and particle trapping. The process therefore exhibits a feedback among rough-wall geometry, flow redistribution, and local proppant deposition.

Overall, proppant placement in the rough fracture is a nonlinear outcome of geometry, fluid transport, and particle interactions. These observations indicate that pumping rate, fluid viscosity, and particle size should be selected jointly to balance suspension, distal transport, and local accumulation. The quantitative analyses in the following sections evaluate these effects using the proposed placement indicators.

3.2. Analysis of the Influence of Pumping Parameters

To better understand how proppant moves and settles in rough fractures, the experimental results are reanalyzed within a unified framework, keeping fracture geometry and conditions consistent. The focus is on how key operational factors—pumping rate, fluid viscosity, particle size, and sand concentration — influence migration distance, sand ridge shape, and effective support area.

Some of the experimental data analyzed in this section were previously reported and are reanalyzed here using the quantitative framework developed in this study.

3.2.1. Effect of Pumping Rate

The effect of pumping rate on proppant transport and placement was investigated at model pumping rates of 0.12, 0.16, 0.20, and 0.24 m³/min. During the pumping-rate comparison, the fracturing-fluid viscosity, proppant size, and sand concentration were maintained at 20 mPa·s, 40/70 mesh, and 100 kg/m³, respectively. According to the Froude-based field-to-model scaling relationship described in Section 2.3, these model pumping rates correspond to field single-cluster pumping rates of approximately 3, 4, 5, and 6 m³/min, respectively.

As shown in **Figure 4**, increasing the pumping rate generally enhanced the longitudinal extension of the deposited proppant ridge. At 0.12 m³/min, proppant deposition was mainly concentrated in the near-well and middle portions of the fracture, and the final ridge length was approximately 17.5 m. When the pumping rate increased to 0.16 m³/min, the ridge length increased slightly to approximately 17.6 m. At 0.20 and 0.24 m³/min, the observed ridge length reached approximately 20.3 m, indicating that the proppant front had reached the distal end of the nominal 20 m observation section. The ridge profiles therefore demonstrate that increasing pumping rate promotes long-distance proppant transport and enhances delivery toward the far-well region.

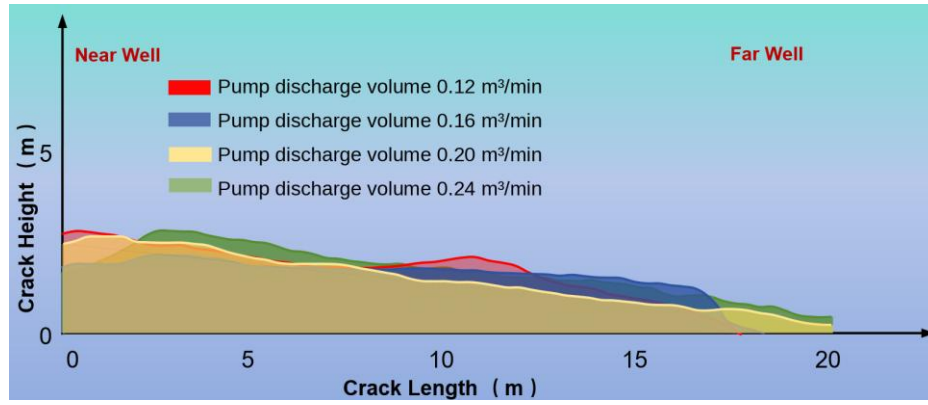


Figure 4. Sand-ridge profiles under different pumping-rate regimes.

The influence of pumping rate can be interpreted from the competition between horizontal fluid transport and gravitational settling of the proppant. Under a simplified Stokes-settling assumption (Bai & Li, 2023), the characteristic horizontal transport distance can be expressed as

$$L = \frac{18Hu\mu}{d_p^2(\rho_p - \rho_f)g} \quad (19)$$

where L is the characteristic horizontal transport distance of the proppant, H is the characteristic vertical settling distance, u is the average horizontal fluid velocity in the fracture, μ is the fluid viscosity, d_p is the characteristic proppant diameter, ρ_p and ρ_f are the proppant and fluid densities, respectively, and g is gravitational acceleration.

For a fracture with fixed aperture and height, the average fracture-flow velocity is expressed as

$$u = \frac{Q}{wH_f} \quad (20)$$

where Q is the pumping rate, w is the fracture aperture, and H_f is the fracture height. Because w , H_f , μ , d_p , ρ_p , and ρ_f remain unchanged among the pumping-rate cases, Equations (19) and (20) indicate the following scaling relationship:

$$L \propto u \propto Q \quad (21)$$

Therefore, increasing the pumping rate increases the average fracture-flow velocity and increases the horizontal distance over which proppant can be transported before substantial gravitational settling occurs. Equation (19) is used here as a simplified physical scaling relationship rather than an exact prediction of proppant transport distance. In the rough fracture, the actual transport process is additionally influenced by surface irregularity, spatially nonuniform flow, particle-wall interactions, and particle-particle interactions.

Figure 5 further shows that increasing pumping rate improves both the transport extent and the overall effective support. The normalized effective supported length, L_{eff}^* , increased from 0.875 at 0.12 m³/min to 0.880 at 0.16 m³/min and reached 1.000 at both 0.20 and 0.24 m³/min. The transition from 0.16 to 0.20 m³/min therefore produced the most evident improvement in distal extension. However, $L_{eff}^* = 1.000$ represents the upper measurable limit imposed by the 20 m observation length. Consequently, the unchanged L_{eff}^* between 0.20 and 0.24 m³/min should not be interpreted as complete saturation of the intrinsic proppant-transport capacity; rather, the deposited-proppant front had already reached the end of the experimental section.

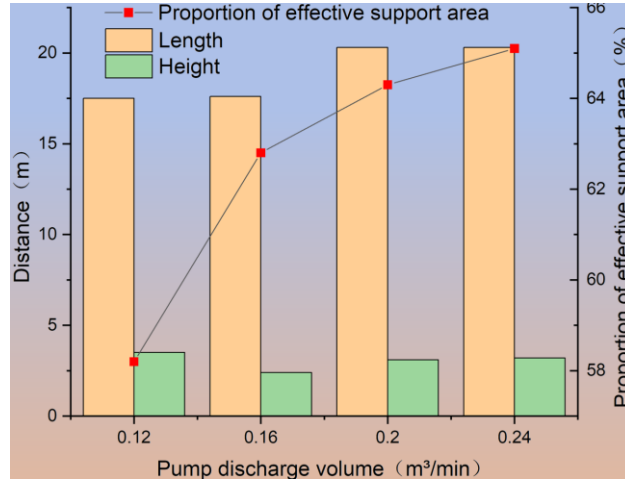


Figure 5. Quantitative comparison of proppant-placement indicators at different pumping rates (prepared by the authors)

The normalized effective supported area, A_{eff}^* , increased from 0.582 at 0.12 m³/min to 0.628 at 0.16 m³/min, 0.643 at 0.20 m³/min, and 0.651 at 0.24 m³/min. The relative increases between successive pumping-rate levels were approximately 7.9%, 2.4%, and 1.2%, respectively. This result indicates that the overall effective support continuously improved with increasing pumping rate, whereas the marginal improvement gradually decreased at higher rates. Therefore, the change between 0.20 and 0.24 m³/min is more appropriately interpreted as diminishing marginal improvement rather than as evidence of a sharply defined pumping-rate saturation threshold.

The distal coverage ratio, D_{cov} , exhibited a clearer monotonic response to pumping rate. D_{cov} increased from 0.026 at 0.12 m³/min to 0.045 at 0.16 m³/min, 0.079 at 0.20 m³/min, and 0.115 at 0.24 m³/min. Consequently, the proportion of deposited proppant located within the distal 20% of the fracture at 0.24 m³/min was approximately 4.4 times that at 0.12 m³/min. More importantly, D_{cov} continued to increase after L_{eff}^* had reached 1.000. This demonstrates that the arrival of the proppant front at the distal boundary does not necessarily represent sufficient distal filling. Even after full-length transport is achieved, increasing pumping rate can continue to increase the amount of proppant deposited in the far-well region.

In contrast, the near-wellbore accumulation ratio, N_{acc} , did not exhibit a monotonic response to pumping rate. N_{acc} was 0.321, 0.271, 0.337, and 0.259 at pumping rates of 0.12, 0.16, 0.20, and 0.24 m³/min, respectively. In particular, the 0.20 m³/min condition exhibited both full-length transport and a relatively high near-wellbore accumulation ratio. This indicates that enhanced distal transport does not necessarily eliminate near-wellbore deposition. Instead, substantial inlet-side accumulation and effective distal transport may occur simultaneously under the same pumping condition.

A similar non-monotonic response was observed for the ridge-height coefficient of variation, CV_h . Its value decreased from 0.338 at 0.12 m³/min to 0.209 at 0.16 m³/min, increased to 0.481 at 0.20 m³/min, and then decreased to 0.290 at 0.24 m³/min. The lowest CV_h at 0.16 m³/min indicates a comparatively uniform deposited-proppant profile, whereas the higher value at 0.20 m³/min reflects stronger spatial variation in ridge thickness. Therefore, increasing pumping rate does not necessarily result in a monotonic improvement in placement uniformity. Full-length transport can coexist with pronounced local variation in deposited-proppant thickness.

Overall, the quantitative results indicate that pumping rate primarily controls the distal transport capability of proppant. Increasing the model pumping rate from 0.12 to 0.24 m³/min increased L_{eff}^* from 0.875 to the observation-limit value of 1.000, increased A_{eff}^* from 0.582 to 0.651, and increased D_{cov} from 0.026 to 0.115. Among these indicators, D_{cov} exhibited the clearest monotonic response, confirming the important role of pumping rate in promoting distal proppant delivery. In contrast, N_{acc} and CV_h varied non-monotonically, indicating that enhanced transport distance does not necessarily correspond to reduced near-wellbore accumulation or improved placement uniformity. Therefore, pumping rate should primarily be regarded as a distal-transport control parameter, while the final spatial distribution of proppant should be evaluated jointly with fluid viscosity, proppant size, sand concentration, and rough-fracture geometry.

3.2.2. Effect of Fracturing-Fluid Viscosity

The effect of fracturing-fluid viscosity on proppant placement was evaluated at viscosities of 10, 20, and 40 mPa·s, corresponding to the low-, medium-, and high-viscosity conditions, respectively. During these tests, the model pumping rate, proppant size, and sand concentration were maintained at 0.16 m³/min, 40/70 mesh, and 100 kg/m³. Therefore, the differences among the three cases mainly reflect the local response of proppant transport and deposition to fluid viscosity.

As shown in **Figure 6**, fluid viscosity strongly affected both the longitudinal extension and geometric morphology of the final proppant ridge. Under the low-viscosity condition of 10 mPa·s, proppant deposition was concentrated mainly in the near-well and middle regions, and the ridge length was approximately 14.5 m. The ridge thickness decreased rapidly along the flow direction, and little effective deposition occurred in the distal section. When viscosity increased to 20 mPa·s, the proppant ridge extended to approximately 17.6 m and became substantially more continuous along the fracture. Increasing the viscosity further to 40 mPa·s did not produce an additional increase in ridge length, which remained approximately 17.6 m. The profiles in **Figure 6** therefore indicate that increasing viscosity from 10 to 20 mPa·s markedly improves proppant suspension and longitudinal transport, whereas the benefit becomes limited when viscosity is further increased.

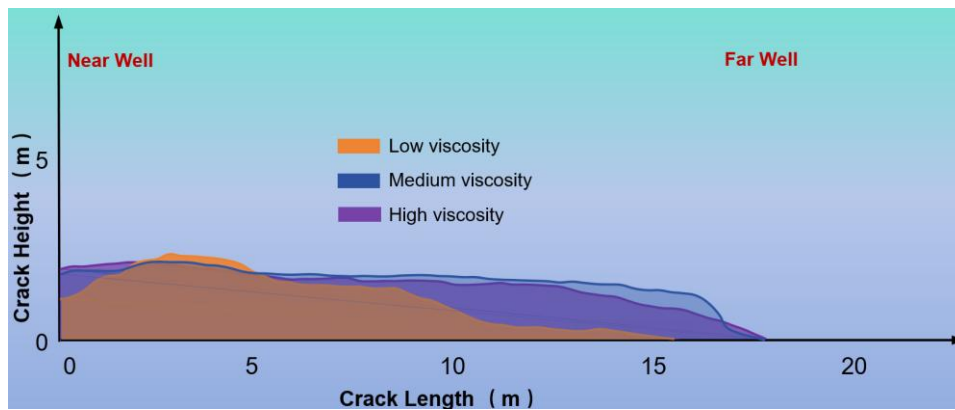


Figure 6. Effect of fluid-viscosity level on final proppant placement profile.

The observed trend is consistent with the competition between particle settling and fluid carrying capacity. According to the simplified transport relationship introduced in Equation (19), the characteristic horizontal transport distance increases with fluid viscosity when the other particle and flow parameters remain unchanged. A higher-viscosity fluid reduces the gravitational settling velocity of the proppant and increases the time available for horizontal transport. However, this relationship represents an idealized scaling trend. In the rough fracture, excessive viscosity may also increase viscous resistance and modify the local velocity distribution, so the improvement in final placement does not necessarily increase proportionally with viscosity.

The quantitative results shown in Figure 7 further demonstrate this transition. The normalized effective supported length, L_{eff}^* , increased from 0.725 under the low-viscosity condition to 0.880 at 20 mPa·s, corresponding to an increase of approximately 21.4%. When viscosity increased further to 40 mPa·s, L_{eff}^* remained at 0.880. A similar response was observed for the normalized effective supported area. A_{eff}^* increased substantially from 0.255 at 10

mPa·s to 0.628 at 20 mPa·s, representing an increase of approximately 146%. However, A_{eff}^* decreased slightly to 0.607 at 40 mPa·s. Therefore, the largest improvement occurred between the low- and medium-viscosity conditions, whereas further viscosity increase produced little additional benefit in either supported length or overall supported area.

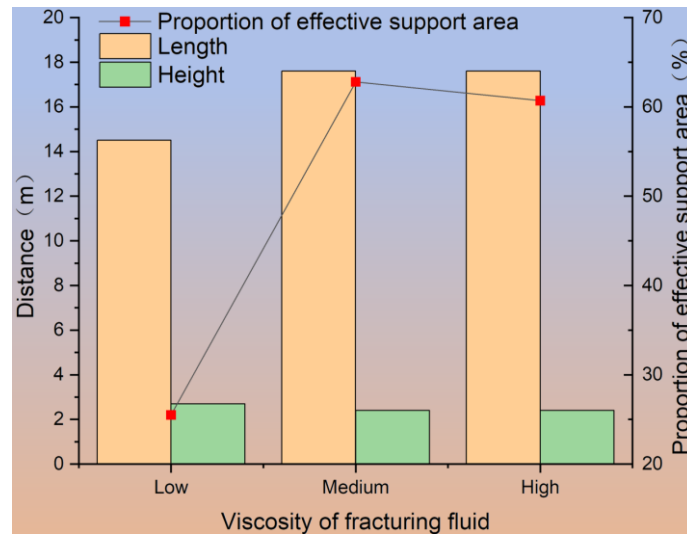


Figure 7. Quantitative comparison of proppant-placement indicators at different fracturing-fluid viscosities.

The spatial placement indicators provide additional evidence for this behavior. Under the low-viscosity condition, N_{acc} reached 0.439, indicating that approximately 43.9% of the deposited-proppant area was concentrated within the near-well evaluation region. At the same time, D_{cov} was approximately zero because the effective proppant ridge did not extend into the final 20% of the fracture. When viscosity increased to 20 mPa·s, N_{acc} decreased markedly to 0.271, while D_{cov} increased to 0.045. These changes indicate that the medium-viscosity fluid reduced inlet-dominated accumulation and redistributed a larger fraction of proppant toward the distal fracture.

When viscosity increased further to 40 mPa·s, N_{acc} increased slightly to 0.306 and D_{cov} decreased to 0.029. Although the high-viscosity fluid maintained a relatively long supported region, its distal filling was somewhat weaker than that obtained at 20 mPa·s. The ridge-height coefficient of variation showed a similar response. CV_h decreased from 0.531 at 10 mPa·s to 0.209 at 20 mPa·s, indicating a substantial improvement in placement uniformity, but subsequently increased to 0.306 at 40 mPa·s. Therefore, the medium-viscosity condition produced the most uniform deposited-proppant profile among the three tested viscosity levels.

Overall, **Figure 6** and **Figure 7** indicate that fluid viscosity controls both proppant suspension and the spatial distribution of deposited particles. Increasing viscosity from 10 to 20 mPa·s substantially increased L_{eff}^* , A_{eff}^* , and D_{cov} while reducing N_{acc} and CV_h , demonstrating improved transport continuity and placement uniformity. Further increasing viscosity to 40 mPa·s maintained the supported length but did not improve the supported area or distal coverage and resulted in a moderate increase in near-wellbore accumulation and profile nonuniformity. Therefore, within the investigated range, the medium-viscosity condition of approximately 20 mPa·s provided the most favorable balance between proppant suspension, distal transport, and placement uniformity. This value should be interpreted as a favorable condition within the present experimental range rather than as a universal optimum viscosity.

3.2.3. Effect of Proppant Particle Size

The effect of proppant particle size on transport and placement was evaluated using 20/40-, 40/70-, and 70/140-mesh quartz sand. During these tests, the model pumping rate, fracturing-fluid viscosity, and sand concentration were maintained at 0.16 m³/min, 20 mPa·s, and 100 kg/m³, respectively. Therefore, the differences among the three cases mainly reflect the local response of proppant transport and deposition to particle size.

As shown in **Figure 8**, proppant size significantly affected both the longitudinal extension and the geometric morphology of the final deposited ridge. The 20/40-mesh proppant formed a relatively thick ridge extending to approximately 20.3 m, indicating that coarse particles could still be transported through nearly the entire observation

section under the tested flow condition. The 40/70-mesh proppant formed a comparatively continuous and smooth ridge with a length of approximately 17.6 m. In contrast, the 70/140-mesh proppant extended to approximately 20.1 m and showed greater distal penetration, although the deposited layer was generally thinner than that formed by the coarser particles. These profiles indicate that particle size affects not only transport distance but also the distribution of deposited proppant along the fracture.

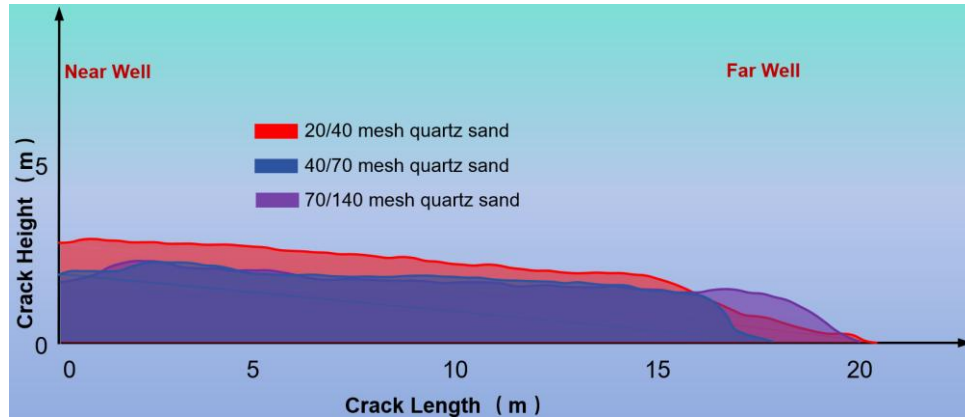


Figure 8. Comparison of proppant-pack geometry for different particle-size ranges.

The particle-size dependence can be interpreted from the competition between horizontal advection and gravitational settling. According to the simplified transport relationship introduced in Equation (19), the characteristic horizontal transport distance is inversely related to the square of the particle diameter when the fluid and flow conditions are fixed. Therefore, a reduction in particle diameter decreases the gravitational settling velocity and generally increases the time available for horizontal transport. This trend helps explain the stronger distal penetration observed for the 70/140-mesh proppant. However, the actual placement pattern in the rough fracture is also affected by particle–wall collision, local surface irregularities, particle concentration, and local velocity variation. Consequently, transport distance alone cannot be used to determine the overall quality of proppant placement.

The quantitative results shown in **Figure 9** further illustrate these differences. The normalized effective supported length, L_{eff}^* , was 1.000 for the 20/40-mesh proppant, 0.880 for the 40/70-mesh proppant, and 1.000 for the 70/140-mesh proppant. Thus, both the coarse 20/40-mesh and fine 70/140-mesh proppants reached the full observation length, whereas the intermediate 40/70-mesh proppant produced a somewhat shorter supported region. In terms of overall support, A_{eff}^* decreased slightly from 0.631 for 20/40 mesh to 0.628 for 40/70 mesh and further to 0.595 for 70/140 mesh. Therefore, the longest transport distance did not correspond to the largest effective supported area.

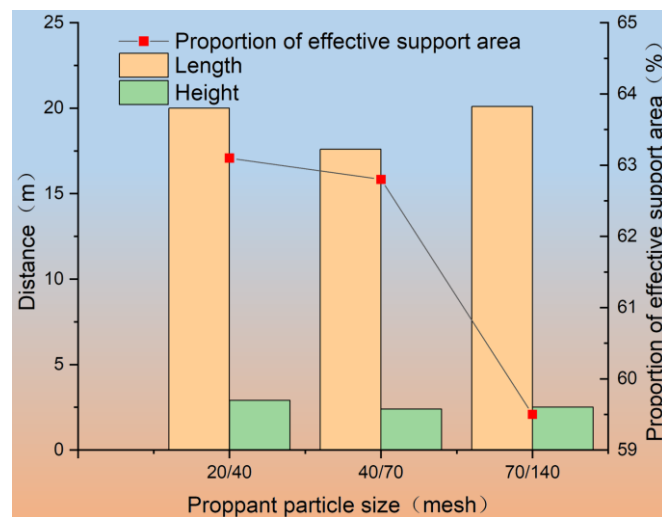


Figure 9. Quantitative comparison of proppant-placement indicators for different proppant sizes (prepared by the authors)

The distal coverage ratio provides additional insight into this difference. D_{cov} increased from 0.075 for 20/40 mesh to 0.137 for 70/140 mesh, whereas the 40/70-mesh case showed a lower value of 0.045. The 70/140-mesh proppant

therefore exhibited the strongest distal coverage among the three particle-size conditions. This result is consistent with its lower settling tendency and indicates that fine particles are more readily transported toward the far-well region. However, the lower A_{eff}^* of 0.595 shows that improved distal penetration does not necessarily produce greater overall filling of the fracture.

The near-wellbore accumulation ratio changed only moderately with particle size. N_{acc} was 0.271 for both the 20/40- and 40/70-mesh proppants and decreased slightly to 0.254 for the 70/140-mesh proppant. This suggests that reducing particle size slightly weakens the relative concentration of deposited proppant near the inlet and promotes redistribution toward the distal region. The ridge-height coefficient of variation also showed clear differences. CV_h was 0.356 for 20/40 mesh, decreased to 0.209 for 40/70 mesh, and increased slightly to 0.229 for 70/140 mesh. Therefore, the 40/70-mesh proppant produced the most uniform ridge-height distribution, whereas the 20/40-mesh proppant exhibited stronger local variation in deposited thickness.

Overall, **Figure 8** and **Figure 9** demonstrate that proppant particle size controls the balance between overall filling, distal transport, and placement uniformity. The 20/40-mesh proppant produced the largest effective supported area but showed comparatively greater variation in ridge height. The 70/140-mesh proppant exhibited the highest distal coverage and lower near-wellbore accumulation, demonstrating superior long-distance transport capability, but its overall effective supported area was lower. The 40/70-mesh proppant produced the lowest CV_h and therefore the most uniform deposited profile among the three tested particle sizes. These results indicate that particle-size selection should not be based solely on transport distance. Within the investigated conditions, 40/70-mesh proppant provided a comparatively favorable balance between effective support and placement uniformity, whereas finer proppant was more advantageous when distal transport was the primary objective.

3.2.4. Effect of Sand Concentration

The effect of sand concentration on proppant placement was evaluated at concentrations of 100, 200, and 300 kg/m³. During these tests, the model pumping rate, fracturing-fluid viscosity, and proppant size were maintained at 0.16 m³/min, 10 mPa·s, and 40/70 mesh, respectively. Therefore, the differences among the three cases mainly reflect the local response of proppant transport and deposition to increasing particle loading.

As shown in **Figure 10**, sand concentration had a pronounced effect on the overall volume and spatial extent of the deposited proppant ridge. At 100 kg/m³, the proppant ridge was mainly concentrated in the near-well and middle portions of the fracture and extended to approximately 14.5 m, with a maximum ridge height of approximately 2.7 m. When the sand concentration increased to 200 kg/m³, the ridge extended to approximately 20.0 m and the maximum height increased to approximately 4.0 m. At 300 kg/m³, the ridge length increased slightly to approximately 20.3 m and the maximum height reached approximately 4.1 m. Thus, increasing sand concentration substantially increased both the amount of deposited proppant and the continuity of support along the fracture.

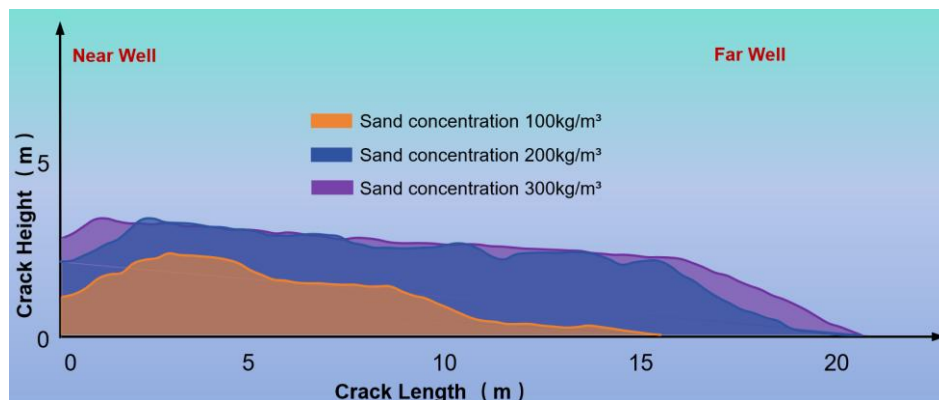


Figure 10. Sand-ridge response to increasing particle loading concentration.

The quantitative results in **Figure 11** further demonstrate this trend. The normalized effective supported length, L_{eff}^* , increased from 0.725 at 100 kg/m³ to 1.000 at both 200 and 300 kg/m³. Similarly, the normalized effective supported area, A_{eff}^* , increased markedly from 0.255 to 0.555 and then to 0.614. The increase from 100 to 200 kg/m³ was

therefore much greater than that from 200 to 300 kg/m³. This indicates that increasing sand concentration from a relatively low level substantially improves fracture filling, whereas the marginal improvement decreases at higher concentrations.

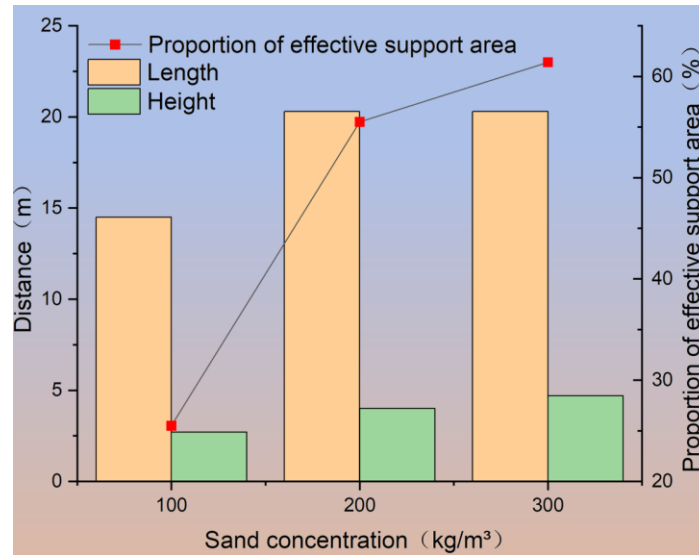


Figure 11. Quantitative comparison of proppant-placement indicators at different sand concentrations.

The spatial placement indicators provide additional information on how the deposited proppant was redistributed. N_{acc} decreased sharply from 0.439 at 100 kg/m³ to 0.249 at 200 kg/m³ and then increased slightly to 0.259 at 300 kg/m³. The high N_{acc} at 100 kg/m³ indicates that a large proportion of the deposited proppant remained concentrated near the fracture inlet. Increasing the concentration to 200 kg/m³ substantially reduced this inlet-dominated distribution and promoted more extensive placement along the fracture. The small increase in N_{acc} from 200 to 300 kg/m³ suggests that further increasing particle loading may begin to enhance local accumulation, although the difference is limited.

A similar transition was observed in the distal coverage ratio. D_{cov} increased from approximately 0 at 100 kg/m³ to 0.094 at 200 kg/m³ and remained nearly unchanged at 0.095 at 300 kg/m³. Therefore, increasing the concentration from 100 to 200 kg/m³ substantially improved distal filling, whereas further increasing the concentration to 300 kg/m³ produced almost no additional improvement in the proportion of proppant deposited in the distal 20% of the fracture. This result indicates that the additional proppant introduced at the highest concentration was mainly accommodated by increasing local ridge thickness rather than by substantially extending distal coverage.

The ridge-height coefficient of variation, CV_h , decreased from 0.531 at 100 kg/m³ to 0.321 at 200 kg/m³ and further to 0.303 at 300 kg/m³. This decrease indicates that increasing particle loading improved the continuity and geometric uniformity of the deposited ridge compared with the low-concentration condition. However, because L_{eff}^* and D_{cov} showed almost no further improvement from 200 to 300 kg/m³, the benefit of the highest concentration was primarily reflected in increased deposited thickness and overall supported area rather than additional distal extension.

Overall, **Figure 10** and **Figure 11** demonstrate that sand concentration primarily controls the filling degree and continuity of proppant placement. Increasing the concentration from 100 to 200 kg/m³ increased L_{eff}^* from 0.725 to 1.000, A_{eff}^* from 0.255 to 0.555, and D_{cov} from 0 to 0.094, while markedly reducing near-wellbore accumulation and profile nonuniformity. Increasing the concentration further to 300 kg/m³ increased A_{eff}^* to 0.614 but produced only minor changes in L_{eff}^* , N_{acc} , and D_{cov} . Therefore, higher sand concentration improves fracture filling, but its marginal benefit for distal transport decreases once full-length placement has been achieved. Under the investigated conditions, excessively increasing particle loading should consequently be evaluated with consideration of potential local accumulation and bridging-prone behavior rather than solely on the basis of total supported area.

3.2.5. Normalized Local Sensitivity of Placement Indicators

To further compare the relative effects of the four operating parameters, the normalized local-sensitivity method described in Section 2.6 was applied to the effective supported area and distal support extension. The sensitivity weights represent the relative response magnitude within the investigated parameter ranges and should not be interpreted as universal physical contribution ratios.

As shown in **Figure 12**, fracturing-fluid viscosity and sand concentration were the two most sensitive parameters affecting the effective supported area. Their normalized local-sensitivity weights were approximately 44.4% and 43.0%, respectively, whereas pumping rate and proppant particle size accounted for only approximately 8.3% and 4.3%. This result indicates that the overall filling degree of the fracture is controlled primarily by the carrying capacity of the fluid and the amount of proppant introduced into the fracture. Increasing fluid viscosity from a low to a moderate level substantially suppresses gravitational settling and improves suspension, thereby increasing the continuity of the deposited ridge. Similarly, increasing sand concentration directly increases the amount of proppant available for fracture filling and produces a substantial increase in effective supported area.

The comparatively low sensitivity weight of pumping rate with respect to A_{eff}^* does not imply that pumping rate is unimportant for proppant transport. As demonstrated in Section 3.2.1, increasing pumping rate strongly promotes distal migration, but once the proppant front approaches the end of the 20.3 m observation section, further increases in rate produce only limited additional growth in the total effective supported area. Therefore, pumping rate mainly affects the spatial extension of placement rather than the total amount of supported area. Proppant particle size shows the lowest sensitivity to A_{eff}^* , indicating that changes in particle size mainly modify the distribution pattern and distal transport behavior rather than causing large changes in the total projected support area.

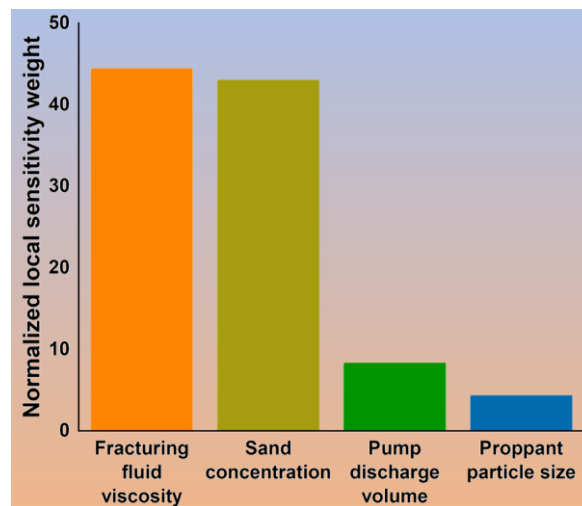


Figure 12. Normalized local sensitivity of effective supported area to operating parameters (prepared by the authors)

A different sensitivity pattern is observed for distal support extension, as shown in **Figure 13**. Pumping rate exhibits the strongest influence on the extension of the proppant-supported region, demonstrating that flow energy and fracture-flow velocity are the primary controls on long-distance particle migration. Increasing pumping rate increases the horizontal carrying velocity and enables particles to travel farther before gravitational settling becomes dominant. Fracturing-fluid viscosity also affects distal extension by modifying particle suspension and settling velocity, whereas proppant particle size produces a secondary effect through the particle-size dependence of gravitational settling.

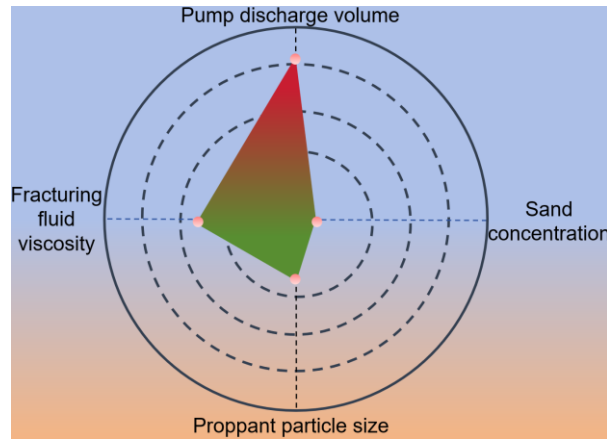


Figure 13. Parameter contribution to distal support extension (prepared by the authors)

The contrast between **Figure 12** and **Figure 13** demonstrates that the factors controlling overall fracture filling are not identical to those controlling distal transport. Fluid viscosity and sand concentration dominate the response of effective supported area, whereas pumping rate plays a more important role in determining the extent of distal support. This distinction is also consistent with the spatial placement indicators discussed in Sections 3.2.1–3.2.4: D_{cov} responds strongly to changes in transport capability, whereas N_{acc} and CV_h reflect more complex interactions among fluid properties, particle loading, particle size, and rough-fracture geometry.

Overall, the normalized local-sensitivity analysis indicates that no single operating parameter simultaneously controls all aspects of proppant placement. Pumping rate should primarily be optimized to ensure sufficient distal transport, whereas fluid viscosity and sand concentration should be adjusted to improve the overall filling degree and continuity of the proppant ridge. Proppant particle size provides an additional means of balancing distal transport and local deposition. Consequently, engineering optimization should consider the combined objectives of effective supported area, distal extension, near-wellbore accumulation, and placement uniformity rather than maximizing any individual parameter alone.

3.3. Classification of Proppant Placement

Based on the final proppant-ridge morphology and the quantitative indicators defined in Section 2.4, the observed proppant-placement behavior was classified into four representative patterns: near-wellbore accumulation, uniform spreading, distal-deficient placement, and bridging-prone high-loading placement. The classification was not based solely on visual observations but on the combined responses of normalized effective supported length (L_{eff}^*), normalized effective supported area (A_{eff}^*), near-wellbore accumulation ratio (N_{acc}), distal coverage ratio (D_{cov}), and ridge-height coefficient of variation (CV_h). The quantitative criteria used to distinguish these patterns are summarized in **Table 5**. Because the present dataset contains ten operating cases, the criteria are intended for comparative engineering evaluation within the investigated conditions rather than as universal regime boundaries.

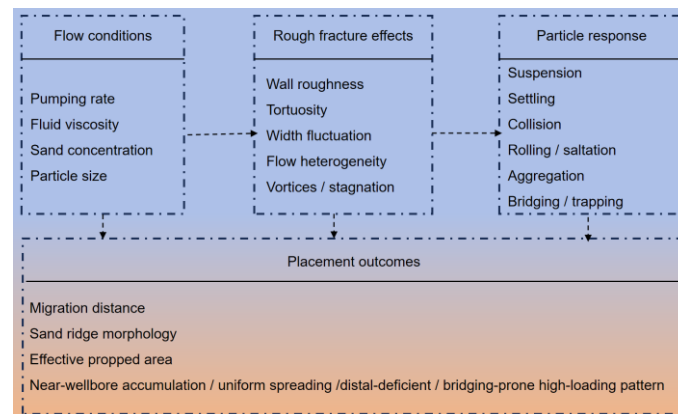
3.3.1. Near-wellbore accumulation pattern

The near-wellbore accumulation pattern is characterized by limited supported length, high inlet-side deposition, low distal coverage, and relatively large variation in ridge height. Case 1 provides the clearest example, with $L_{eff}^* = 0.725$, $A_{eff}^* = 0.255$, $N_{acc} = 0.439$, $D_{cov} = 0$, and $CV_h = 0.531$. Approximately 43.9% of the deposited proppant was concentrated in the near-well region, while essentially no effective deposition occurred within the distal 20% of the fracture. According to the criteria in **Table 5**, the combination of high N_{acc} , low D_{cov} , and reduced L_{eff}^* therefore represents a dominant near-wellbore accumulation tendency.

Table 5.Quantitative criteria for placement-pattern classification.

Placement pattern	L_{eff}^*	A_{eff}^*	N_{acc}	D_{cov}	CV_h / supplementary feature
Near-wellbore accumulation	Low–moderate	Low–moderate	High	Low	Often high
Uniform spreading	High	High	Low–moderate	High	Low
Distal-deficient	Low–moderate	Moderate–high	Moderate	Low	Variable
Bridging-prone high-loading	High/variable	High	Variable	Variable	High local ridge thickness

This pattern generally reflects insufficient proppant transport relative to gravitational settling. As illustrated in **Figure 14**, pumping conditions first interact with fracture roughness and local geometric heterogeneity, which subsequently influence particle suspension, settling, collision, and trapping. When the carrying capability is insufficient, these effects promote early deposition and cause the proppant ridge to decay rapidly along the flow direction.

**Figure 14.** Conceptual framework linking operating conditions, rough-fracture effects, particle responses, and proppant-placement patterns.

3.3.2. Uniform spreading pattern

Uniform spreading is characterized by relatively large supported length and area, sufficient distal coverage, limited near-wellbore accumulation, and comparatively small ridge-height variation. Cases 3 and 10 exhibit representative characteristics of this pattern. Case 3 has $L_{eff}^* = 1.000$, $A_{eff}^* = 0.614$, $N_{acc} = 0.259$, $D_{cov} = 0.095$, and $CV_h = 0.303$, whereas Case 10 has $L_{eff}^* = 1.000$, $A_{eff}^* = 0.651$, $N_{acc} = 0.259$, $D_{cov} = 0.115$, and $CV_h = 0.290$.

As summarized in **Table 5**, full-length transport alone is insufficient to identify uniform placement. A relatively high D_{cov} must be accompanied by limited N_{acc} and a relatively low CV_h . This combination indicates that proppant is not only transported to the distal region but is also distributed comparatively continuously along the fracture. In the framework shown in **Figure 14**, this pattern represents a relatively balanced state between particle suspension, settling, fracture-induced disturbance, and deposition.

3.3.3. Distal-deficient placement pattern

The distal-deficient pattern describes conditions in which a considerable amount of proppant is deposited within the near-well and middle portions of the fracture, but effective support toward the far-well region remains insufficient. Cases 4, 6, and 8 exhibit this characteristic to different degrees. Their L_{eff}^* values range from 0.875 to 0.880, while D_{cov} remains between only 0.026 and 0.045.

Case 6 is particularly illustrative. Although A_{eff}^* reaches 0.628 and CV_h is only 0.209, indicating relatively high overall filling and good uniformity within the supported region, L_{eff}^* is only 0.880 and D_{cov} is 0.045. Thus, a uniform ridge within the deposited region does not necessarily guarantee adequate distal support. According to **Table 5**, distal-deficient placement is therefore identified primarily by insufficient L_{eff}^* and/or low D_{cov} rather than by effective supported area alone.

As indicated in **Figure 14**, this behavior results from the combined effects of flow conditions, fracture roughness, and particle response. Proppant may remain well suspended and relatively uniformly distributed over part of the fracture while still undergoing sufficient settling or trapping to prevent adequate filling of the distal region.

3.3.4. Bridging-prone high-loading pattern

At high particle loading, a different placement response may develop in which the deposited ridge becomes locally thick and particle crowding becomes more pronounced. The 300 kg/m³ condition is representative of this tendency. In this case, L_{eff}^* reaches 1.000 and A_{eff}^* reaches 0.614, while the maximum ridge height is approximately 4.1 m, corresponding to about 91% of the 4.5 m fracture height. Although D_{cov} remains approximately 0.095, the large local ridge thickness indicates that additional injected proppant is increasingly accommodated through local vertical accumulation rather than further distal extension.

According to **Table 5**, this pattern is identified using high particle loading and pronounced local ridge development as supplementary criteria in addition to the normalized placement indicators. As shown schematically in **Figure 14**, increasing particle concentration enhances particle–particle interaction, aggregation, collision, and trapping, which may increase the likelihood of local flow-path restriction.

Because stable mechanical bridging was not independently verified in the present experiments, this pattern is termed bridging-prone high-loading placement rather than confirmed bridging. This distinction avoids interpreting local high-concentration accumulation as direct evidence of complete fracture blockage.

3.3.5. Transition among placement patterns

The four placement patterns should not be regarded as completely independent or fixed states. Changes in pumping rate, fluid viscosity, sand concentration, or particle size can shift the balance among suspension, settling, collision, trapping, and distal transport, resulting in transitions from one dominant placement pattern to another. **Figure 14** summarizes this interaction: operating conditions act together with rough-fracture characteristics to control particle-scale responses, which ultimately determine migration distance, ridge morphology, supported area, and placement pattern.

The quantitative criteria summarized in **Table 5** therefore provide a practical means of identifying the dominant placement characteristic of each operating condition. More importantly, the classification demonstrates that a single indicator cannot fully describe proppant-placement quality. A large A_{eff}^* may coexist with insufficient distal support, while full-length transport may occur together with substantial near-wellbore accumulation or local thickness variation. Consequently, L_{eff}^* , A_{eff}^* , N_{acc} , D_{cov} , and CV_h should be considered jointly when evaluating proppant placement and selecting operating parameters.

3.4. Exploratory Empirical Correlation for Effective Supported Area

To quantitatively summarize the combined effects of operating parameters on the overall proppant-placement response, an exploratory empirical correlation was developed for the normalized effective supported area, A_{eff}^* . Four operating parameters were considered: pumping rate Q , fracturing-fluid viscosity μ , sand concentration C_m , and characteristic proppant diameter d_p . Because the same rough-fracture geometry and roughness realization were used for all ten experimental cases, fracture roughness was treated as a fixed geometric boundary condition rather than an independently regressed variable. Therefore, the correlation developed here is specific to the investigated rough-fracture geometry and is not intended to represent a universal roughness-dependent relationship.

A dimensionless multiplicative power-law form was adopted to describe the combined response of A_{eff}^* to the four operating parameters:

$$\frac{A_{eff}}{A_0} = K \times \left(\frac{Q}{Q_0}\right)^{\beta_Q} \times \left(\frac{\mu}{\mu_0}\right)^{\beta_\mu} \times \left(\frac{C_m}{C_{m0}}\right)^{\beta_C} \times \left(\frac{d_p}{d_{p0}}\right)^{\beta_d} \quad (22)$$

where A_0 is the normalized effective supported area under the reference condition; Q_0 , μ_0 , C_{m0} , and d_{p0} are the corresponding reference values; K is a dimensionless regression coefficient; and β_Q , β_μ , β_C , and β_d are the fitted response exponents for pumping rate, fluid viscosity, sand concentration, and particle diameter, respectively. Case 6 was used as the reference condition, with $A_0 = 0.628$, $Q_0 = 0.16$ m³/min, $\mu_0 = 20$ mPa·s, and $C_{m0} = 100$ kg/m³. The representative physical particle diameter was used for the particle-size term rather than the mesh number itself, because mesh number is inversely related to actual particle diameter (Chun et al., 2020; Du et al., 2026).

For coefficient estimation, Equation (22) was transformed into logarithmic form:

$$\ln\left(\frac{A_{eff}}{A_0}\right) = \ln K + \beta_Q \cdot \ln\left(\frac{Q}{Q_0}\right) + \beta_\mu \cdot \ln\left(\frac{\mu}{\mu_0}\right) + \beta_C \cdot \ln\left(\frac{C_m}{C_{m0}}\right) + \beta_d \cdot \ln\left(\frac{d_p}{d_{p0}}\right) \quad (23)$$

The coefficients were obtained by least-squares regression using the ten available experimental cases. The fitted relationship was

$$\frac{A_{eff}}{0.628} = 0.874 \times \left(\frac{Q}{0.16}\right)^{0.295} \times \left(\frac{\mu}{20}\right)^{0.607} \times \left(\frac{C_m}{100}\right)^{0.524} \times \left(\frac{d_p}{d_{p0}}\right)^{0.042} \quad (24)$$

The regression coefficients and their uncertainties are summarized in **Table 6**. The fitted exponents were 0.295 for pumping rate, 0.607 for fluid viscosity, 0.524 for sand concentration, and 0.042 for particle diameter. Among these terms, fluid viscosity and sand concentration exhibited the larger fitted exponents, whereas particle diameter showed a comparatively weak fitted response. However, the confidence intervals of all four exponents were relatively wide and included zero. For example, the 95% confidence interval of β_Q was -0.895 to 1.485 , and that of β_d was -0.603 to 0.688 . This indicates that the limited ten-case dataset does not permit precise identification of the individual multivariable exponents, and the fitted coefficients should therefore not be interpreted as universal physical constants.

The goodness-of-fit statistics further illustrate the limited explanatory capability of the four-factor power-law relationship. As shown in **Table 6**, the logarithmic regression yielded $R^2 = 0.573$ and an adjusted $R^2 = 0.231$. The RMSE of the fitted A_{eff}^* values was 0.095, while the MAPE was 15.07%. The moderate R^2 and substantially lower adjusted R^2 indicate that part of the apparent fit is associated with the relatively large number of fitted parameters compared with the small number of experimental cases. In addition, the experimental trends described in Sections 3.2.1–3.2.4 are not strictly monotonic. In particular, A_{eff}^* increased markedly when viscosity increased from 10 to 20 mPa·s but decreased slightly when viscosity increased further to 40 mPa·s. Such behavior cannot be fully represented by a simple monotonic power-law term (Wang et al., 2018).

To evaluate whether the apparent in-sample fit could be retained when individual cases were excluded from calibration, leave-one-out cross-validation (LOOCV) was performed. In each iteration, one of the ten experimental cases was removed, the correlation was recalibrated using the remaining nine cases, and the excluded case was then predicted. This procedure was repeated ten times so that each experimental case served once as an internal validation sample. The LOOCV prediction error was evaluated using RMSECV, MAPECV, and the predictive coefficient Q^2 .

$$RMSECV = \sqrt{\frac{\sum (A_{eff,i} - \hat{A}_{eff,-i})^2}{n}} \quad (25)$$

$$MAPECV = \frac{100\%}{n} \times \sum \left| \frac{A_{eff,i} - \hat{A}_{eff,-i}}{A_{eff,i}^*} \right| \quad (26)$$

$$Q^2 = 1 - \frac{\sum (A_{eff,i} - \hat{A}_{eff,-i})^2}{\sum [A_{eff,i}^* - \text{mean}(A_{eff}^*)]^2} \quad (27)$$

where $A_{\text{eff},i}$ is the measured normalized effective supported area of Case i , and $\hat{A}_{\text{eff},-i}$ is the corresponding prediction obtained from a model calibrated without Case i .

The internal-validation results are also listed in **Table 6**. LOOCV produced $\text{RMSECV} = 0.294$ and $\text{MAPECV} = 40.79\%$, both substantially larger than the in-sample errors. The predictive coefficient was $Q^2 = -6.074$, indicating that the correlation has poor internal predictive stability when individual experimental cases are excluded from calibration. This behavior is clearly illustrated in **Figure 15**, which compares the measured A_{eff}^* values with the corresponding LOOCV predictions. The dashed 1:1 line represents perfect agreement between measurement and prediction. Although several cases remain relatively close to the agreement line, substantial deviations are evident for some cases, particularly Case 8, for which the model considerably overpredicts A_{eff}^* . The strong deviation of this high-viscosity case further confirms that the simple power-law form cannot adequately capture the observed non-monotonic viscosity response.

Table 6. Regression coefficients and internal-validation statistics for the effective-supported-area correlation.

Item	Value	Standard error	95% confidence interval
K	0.874	0.078	0.696–1.098
β_Q	0.295	0.463	−0.895–1.485
$B\mu$	0.607	0.245	−0.023–1.238
β_C	0.524	0.277	−0.186–1.235
β_d	0.042	0.251	−0.603–0.688
R^2	0.573	—	—
Adjusted R^2	0.231	—	—
RMSE	0.095	—	—
MAPE	15.07%	—	—
LOOCV RMSE	0.294	—	—
LOOCV MAPE	40.79%	—	—
LOOCV Q^2	−6.074	—	—

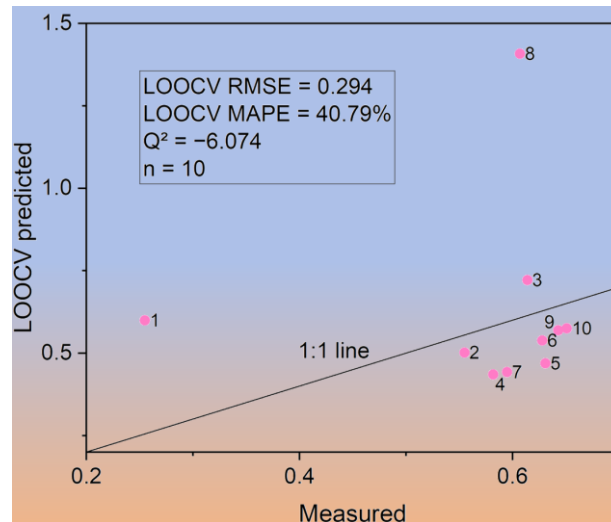


Figure 15. Comparison between measured and LOOCV-predicted normalized effective supported areas. The dashed line represents the 1:1 agreement line.

The LOOCV results are important for defining the appropriate interpretation of Equation (24). The correlation should not be considered a validated predictive model. Instead, it provides an exploratory mathematical summary of the overall response of the present experimental dataset. This distinction is also important when comparing the regression coefficients with the normalized local-sensitivity weights presented in Section 3.2.5. The regression exponents β_Q , β_μ , β_C , and β_d are obtained from simultaneous multivariable fitting, whereas the percentages shown in **Figure 12** describe normalized local response magnitudes within the investigated parameter ranges. The two quantities therefore have different statistical and physical meanings and should not be used interchangeably.

The limited predictive performance is mainly associated with three characteristics of the available dataset. First, only ten experimental cases are available, whereas four operating variables are included in the correlation. Second, the experimental matrix consists primarily of local one-factor comparisons rather than a complete factorial design, limiting the ability to identify parameter interactions. Third, only one rough-fracture geometry was investigated, so the effect of roughness cannot be independently calibrated or validated. Consequently, the individual parameter trends, normalized local-sensitivity analysis, and quantitative placement-pattern classification developed in the preceding sections provide a more robust basis for engineering interpretation than direct extrapolation of Equation (24).

Overall, the proposed correlation is retained as a preliminary and geometry-specific exploratory relationship for summarizing effective supported area within the investigated experimental range. The internal cross-validation demonstrates that its predictive capability is currently insufficient for extrapolation beyond the available dataset. Independent experiments, additional combinations of operating parameters, different roughness realizations, or field-scale placement observations would be required before the correlation could be developed into a more general predictive model.

3.5. Applicability and Limitations

The results of this study should be interpreted within the geometric and operating ranges represented by the present large-scale experiments. The proposed quantitative placement indicators and classification framework were developed using a 20.3 m $\times$ 4.5 m $\times$ 10 mm rough-fracture model, with pumping rate, fluid viscosity, proppant size, and sand concentration varied over the ranges investigated in the ten experimental cases. Therefore, the derived trends are most applicable to fracture geometries, fluid systems, and operating conditions similar to those considered in this study. Extrapolation to substantially different fracture apertures, heights, roughness characteristics, fluid rheology, or proppant systems should be performed cautiously.

A first limitation is the size and structure of the experimental dataset. Only ten operating cases were available, and the experimental matrix consisted mainly of local one-factor comparisons rather than a complete factorial design. Consequently, the individual effects of pumping rate, viscosity, sand concentration, and particle size can be compared

within their respective local reference conditions, but higher-order interactions among these parameters cannot be fully identified. For this reason, the normalized local-sensitivity weights presented in Section 3.2.5 should be interpreted as relative response measures within the tested ranges rather than universal physical contribution ratios.

A second limitation concerns experimental repeatability. Because of the large physical scale, fluid consumption, and material requirements of the 20.3 m fracture system, independent repeated experiments were not available for all operating conditions. Therefore, the uncertainty analysis in Section 2.5 quantifies measurement uncertainty, within-test operating fluctuations, image calibration error, and proppant-boundary extraction uncertainty rather than between-test repeatability. Differences among cases that are comparable to the estimated uncertainty range should consequently be interpreted as tendencies rather than statistically established differences.

A third limitation is associated with fracture roughness. The same reconstructed rough-fracture geometry was used for all ten cases, and roughness was therefore treated as a fixed geometric boundary condition rather than an independently varied experimental parameter. Although the present results demonstrate how operating conditions interact with a representative rough fracture, they do not establish a general quantitative relationship between roughness magnitude and proppant placement. Additional experiments involving different roughness amplitudes, spatial distributions, or fracture geometries would be required to isolate the independent effect of roughness.

The field-to-model scaling also imposes an applicability constraint. Froude similarity was adopted as the primary dynamic-similarity criterion to preserve the relative balance between flow inertia and gravitational settling, whereas Reynolds number was used only as an auxiliary flow-regime consistency parameter. Exact simultaneous similarity of both dimensionless groups was not achieved because the field and model fracture apertures and fluid properties were maintained at the same values. Accordingly, the experimental system should be regarded as a field-representative large-scale physical model rather than a strictly geometrically and dynamically scaled reproduction of the complete field fracture.

The exploratory empirical correlation developed in Section 3.4 has additional limitations. Although the in-sample regression yielded a moderate fit, the leave-one-out cross-validation results showed limited predictive robustness, with a LOOCV RMSE of 0.294, a LOOCV MAPE of 40.79%, and a negative predictive coefficient of $Q^2 = -6.074$. Therefore, the correlation should not be regarded as a validated predictive model. It is retained only as a preliminary, geometry-specific mathematical summary of the available dataset. Independent experimental data or field-scale placement observations are required before the correlation can be used for broader prediction.

Finally, the placement indicators developed in this work describe the geometric distribution of deposited proppant rather than post-closure fracture performance. Parameters such as A_{eff}^* , L_{eff}^* , N_{acc} , D_{cov} , and CV_h quantify filling degree, transport extent, near-wellbore accumulation, distal coverage, and geometric uniformity, respectively, but they do not directly represent fracture conductivity, proppant crushing resistance, embedment, or load-bearing performance under closure stress. Therefore, the proposed framework is primarily intended for evaluating proppant transport and placement quality before fracture closure.

Overall, the present study provides a quantitative framework for comparing proppant-placement behavior under large-scale rough-fracture conditions, but its conclusions should remain bounded by the available experimental geometry and parameter ranges. The quantitative indicators and placement classification are more suitable for comparative engineering evaluation than direct universal prediction. Future validation using additional parameter combinations, different roughness realizations, independent experiments, and field observations would be required to extend the applicability of the proposed framework.

4. Conclusion

Based on the reanalysis of the large-scale rough-fracture experiments, a quantitative framework was established to evaluate proppant placement using normalized effective supported area, supported length, near-wellbore accumulation, distal coverage, and placement uniformity. The main conclusions are as follows:

(1) Pumping rate primarily controls distal proppant transport. Increasing the model pumping rate from 0.12 to 0.24 m³/min increased the normalized supported length from 0.875 to 1.000 and the distal coverage ratio from 0.026 to

0.115. However, the improvement in effective supported area gradually decreased at higher pumping rates, indicating diminishing marginal benefit.

(2) Fluid viscosity and sand concentration mainly affect the overall filling degree and continuity of proppant placement, whereas particle size controls the balance between distal transport and local deposition. Within the investigated conditions, medium-viscosity fluid provided a favorable balance between transport and placement uniformity, while increasing sand concentration mainly improved fracture filling. The combined use of L_{eff}^* , A_{eff}^* , N_{acc} , D_{cov} , and CV_h enables quantitative distinction among near-wellbore accumulation, uniform spreading, distal-deficient, and bridging-prone high-loading patterns.

(3) The exploratory four-factor correlation yielded moderate in-sample fitting performance but limited internal predictive robustness, as indicated by the LOOCV results. Therefore, the correlation should be regarded as a geometry-specific summary of the present dataset rather than a validated predictive model. The proposed quantitative indicators and classification framework are more suitable for comparative engineering evaluation, while broader application requires further independent validation.

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Ethics approval

Not applicable.

Conflict of interest

The authors declare that they have no competing interests.

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