

Experimental Evaluation of Jet Impact Behavior in Large-Diameter Grouting Using Stream Testing

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ABSTRACT: Jet grouting is a widely adopted ground improvement method known for its adaptability in various soil conditions and its effectiveness in creating soil–cement columns. However, the efficiency and quality of jet grouting remain highly dependent on precise control of operational parameters and equipment conditions. This study evaluates the performance of large-diameter jet grouting using a series of controlled stream tests to investigate the influence of injection pressure, flow rate, nozzle diameter, and impact distance on jetting behavior. Tests were conducted with both new and deteriorated nozzles to assess the effects of wear on jet performance. The impact forces were measured across multiple distances and offsets from the nozzle axis using a load cell system. The results established a strong correlation between injection parameters and jet impact force, quantified the reduction in efficiency due to nozzle deterioration, and determined attenuation coefficients that describe the loss of jet intensity with distance. The relationship between pressure and flow rate was also analyzed using principles of fluid mechanics. These findings support the development of empirical models for predicting jet performance and provide practical guidance for quality control and equipment maintenance. The stream test methodology offers an efficient approach for evaluating jetting tools in large-diameter jet grouting operations.

KEYWORDS: Stream test, jet grouting, ground improvement, quality control, attenuation coefficient.

1 INTRODUCTION

Jet grouting has become an indispensable method in modern ground improvement, particularly for applications involving soil stabilization, seepage control, and foundation reinforcement. The technique utilizes high-pressure fluid injection to break up and mix in-situ soils with grout, forming soil–cement columns that can vary in size and strength depending on design parameters. Although jet grouting technology has seen steady advancements, especially in equipment and construction techniques, consistent quality control remains a persistent challenge in ensuring optimal field performance. Large-diameter jet grouting techniques have recently gained attention due to their potential to reduce the number of boreholes, increase productivity, and improve structural performance. These methods are especially relevant in urban infrastructure projects, where minimizing disruption and ensuring robust ground improvement are critical. For instance, large-diameter jet grouting has been employed in complex subsurface construction such as tunnel cross-passages, where ground stability is essential to safety and performance (Jayasiri et al., 2022).

In response to these challenges, this study investigates the efficiency of large-diameter jet grouting through systematic stream testing. Two nozzle types, with diameters of 3.1 mm and 4.3 mm, were examined at various distances and offsets to simulate field performance. Both new and deteriorated nozzles were tested to analyze how wear affects jet intensity and distribution. The results aim to establish clear relationships between jetting parameters and impact force, providing insights for improved equipment design, predictive modeling, and quality control protocols for large-scale jet grouting operations.

2 LARGE-DIAMETER JET GROUTING

A large-diameter jet grouting technique, known as the Rapid-Jet method, was developed in the jet grouting industry within the last decade (Cheng et al., 2012; Silva et al., 2020; Sarkar et al., 2022; Neaupane et al., 2023). The Rapid-Jet method utilizes high-pressure grout slurry to erode and mix the in-situ soil to form soil–cement mixture columns. A double-tube grouting system with two nozzles on the opposite side of the jetting device can carry out efficient grouting with large-diameter and high-speed construction. Figure 1 shows the sketch of the large-diameter jet grouting system.

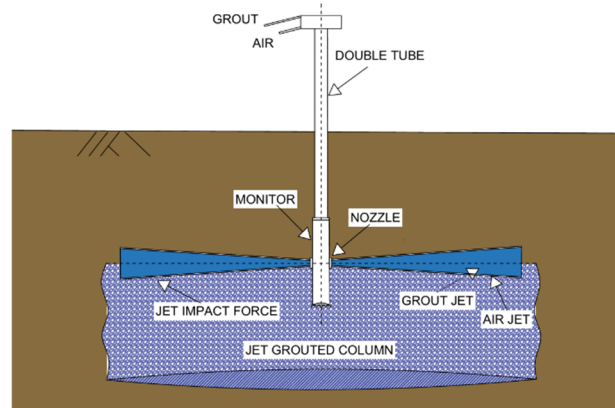


Figure 1. Large-Diameter Jet Grouting.

In recent years, significant advancements have been made in jet grouting technology, particularly in expanding the diameter of jet grout columns and improving associated equipment (Cheng, et al., 2023; Yamazaki, et al., 2024; Shakya, et al., 2025). The Rapid-Jet method utilizes a large nozzle

diameter of 3.1 to 4.3 mm, allowing for a high flow rate that supports high pressure, improves cutting potential, and enables the formation of a large-diameter grouting column with a diameter up to approximately 3.5 m. The parameters that affect the performance of the jet grouted columns include the number of nozzles, nozzle diameter, properties of the injected fluids, eroding time, rotation speed, grout, grout pressure, grout flow rate, air pressure, and air flow rate (Croce, et al., 2014). Table 1 summarizes the jet grouting parameters provided in JJGA (2017) and Rapid-Jet Association (2019). In this study, the operational parameters shown in Table 1 were evaluated using stream tests, which are discussed in the following section.

Table 1. Rapid-Jet standard construction specifications.

Type	R1	R2
Column Diameter (m)	2 – 3	3 – 3.5
Drilling method	Direct drilling	Direct drilling
Installation method	Double tube	Double tube
Grout Pressure (MPa)	30 – 34	30 – 34
Grout flow rate (L/min)	120 – 260	300 – 380
Air pressure (MPa)	0.7 – 1.1	0.7 – 1.1
Air flow rate (m ³ /min)	Over 6	Over 10
1 step (cm)	2.5	2.5
Lift rate (min/m)	10 – 12	10 – 12

3 STREAM TEST EQUIPMENT AND PROCEDURE

The stream test method evaluates the performance of fluid ejection from the nozzle at high injection pressures by assessing the jet impact efficiency. This evaluation focuses on the operational parameters of the jet process, including nozzle diameter, jet pressure, flow rate, air pressure, air flow rate, and distance, as well as the quality of nozzle efficiency and the overall impact of the jetting process at the centerline and epicenter. A list of the equipment and tools required for conducting the stream tests is provided in Figure 2.

The stream tests involve injecting fluid from the nozzle of a jet grouting machine onto a load cell sensor. The fluid pressure was recorded using an indicator. Figure 3 presents the procedure of the stream testing. The stream tests were conducted systematically to evaluate the behavior of pressurized grout as it passed through each load cell, as illustrated in Figure 4. The nozzle operates by converting the pump-generated pressure into the kinetic energy of a high-velocity water jet, which is directed along the stream wise axis at distances ranging from 75 cm to 300 cm from the nozzle outlet. The experimental setup was repeated for each distance, with a consistent epicenter offset of up to 7.5 cm in 2.5 cm increments. A load cell system was sequentially positioned along the x-axis and at the epicenter, forming an orthogonal spatial configuration centered at the nozzle exit. A pressure gauge was used throughout the experiment to monitor and regulate the injection pressure, ensuring the jet fluid was ejected to the observation targets as designed.

The observation points were collected one by one throughout the load cell sensor at each distance, with a consistent epicenter offset of 2.5 cm, 5.0 cm, and 7.5 cm. Each nozzle was tested at ten specific impingement distances: 75, 100, 125, 150, 175, 200, 225, 250, 275, and 300 cm from the nozzle to the receiving surface. Sensor plates were placed at each of these intervals to measure the corresponding impact forces, as illustrated in Figure 5.



Figure 2. List of equipment and tools for the stream tests.

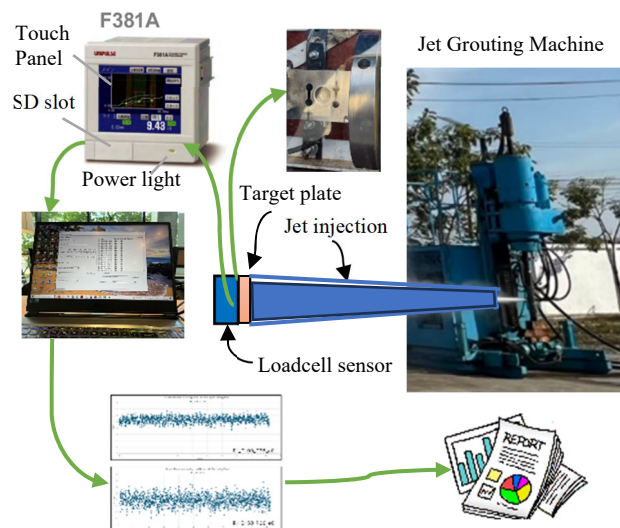


Figure 3. Procedure of stream testing.



Figure 4. Load cell system for the stream tests.

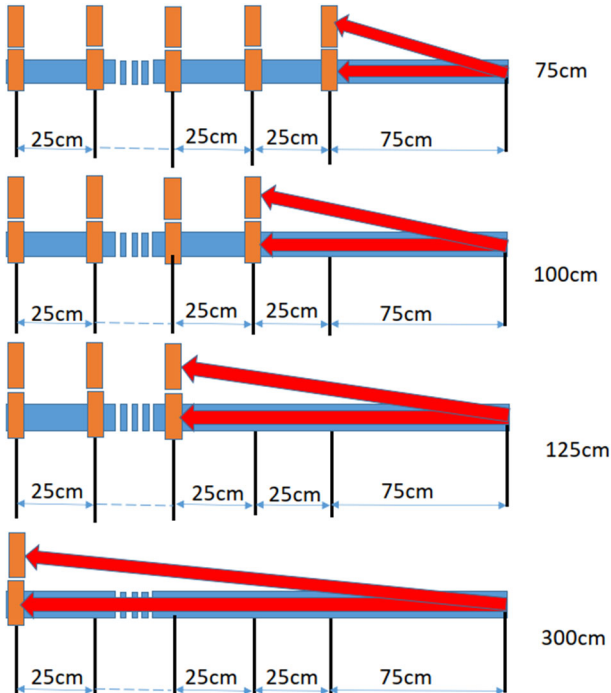


Figure 5. Diagram of the stream test observation points.

This study intends to examine the importance of developing a customized testing methodology that employs water as the primary medium for air-based evaluations, as illustrated in Figure 6. It is observed in Figure 6 that the jet ejection exhibits a fan-shaped pattern, characterized by a small radius at short distances and a progressively increasing size with greater distance. This observation suggests that the boundary of the jet's potential quality can be effectively controlled and enhanced. Based on this concept, our experimental testing approach was designed to yield valuable outcomes for jet grouting quality control, both in industry applications and advancements in geotechnical research.



Figure 6. Photo of jet ejection performance.

4 RESULTS OF STREAM TESTS

4.1 Jet impact force vs time

A batch of raw impact force data recorded in the load cell indicator was processed and plotted to evaluate the trend and shape of the stream behavior. Figures 7 to 9 present the variation of jet recording force over time during turbulent flow at distances of 100 cm, 200 cm, and 300 cm, respectively. These figures indicate that the recorded force decreases as turbulence increases. The data from a shorter distance (100 cm), shown in Figure 7, shows higher force values with a more uniform distribution of points, indicating a relatively stable flow. As the distance increases to 200 and 300 cm (refer to Figures 8 and 9), the force values gradually decrease, and the data points become more dispersed, indicating greater fluctuations in force. This pattern suggests that the jet loses momentum over distance, resulting in increased turbulence and instability in the flow.

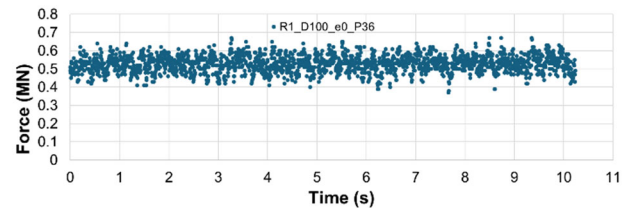


Figure 7. Observed jetting impact force vs time at 100 cm.

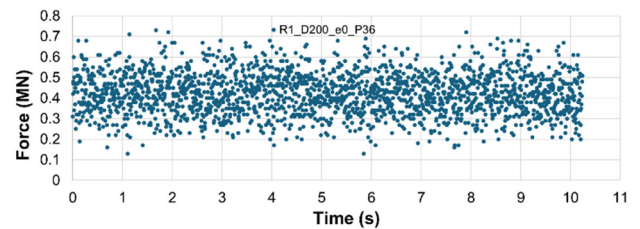


Figure 8. Observed jetting impact force vs time at 200 cm.

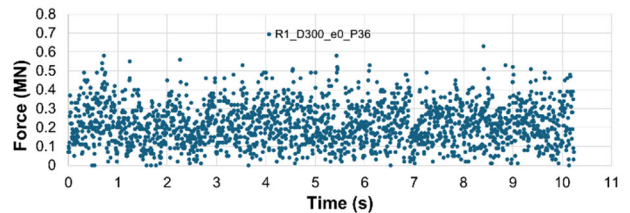


Figure 9. Observed jetting impact force vs time at 300 cm.

4.2 Jet impact force vs distance

Based on the results of the impact force plots presented in the previous section, the fluid jet diminishing force graphs, which are described as collision force versus the distance and decrease by offset from the center of each design pressure set, were plotted. Figures 10 and 11 show the jet impact force for single nozzle types R1 and R2, respectively (refer to Table 1 for nozzle types R1 and R2).

Figures 10 and 11 indicate that the collision force decreases as the distance increases, suggesting a loss of jet impact strength with distance. The nozzle type R2, with higher pressure and flow rates (36 MPa at 119 L/min), generates a greater initial force but experiences a steeper decline than the nozzle type R1, which operates under lower pressure conditions (15 MPa at 78 L/min). The latter maintains lower but more stable force values. Figures 10 and 11 also indicate that as the distance increases, the force values for all conditions gradually converge, indicating a limit beyond which pressure differences have a lesser impact. These highlight the importance of

selecting appropriate pressure and flow rate settings for specific application requirements, as well as controlling jet force over varying distances.

Figure 12 presents the comparison of the jet impact force observed at the offset from the center at various distances from the nozzle location. It is observed in Figure 12 that the jet impact force diminishes dramatically away from the centerline of the jetting. The jet impact force was measured to be nearly zero at a distance of approximately 10 cm from the centerline for all cases monitored.

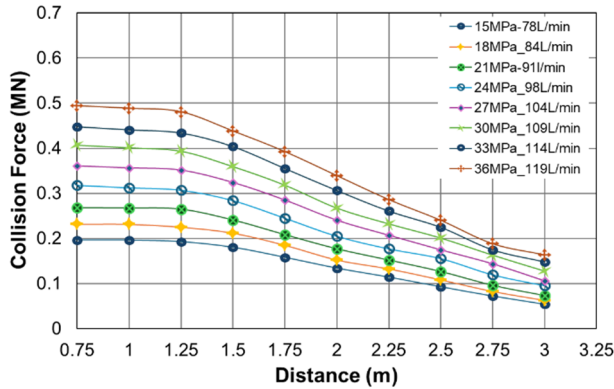


Figure 10. Measurement of jet impact force for single nozzle type R1.

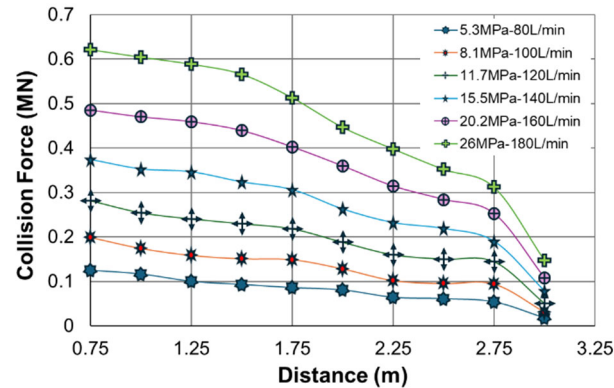


Figure 11. Measurement of jet impact force for single nozzle type R2.

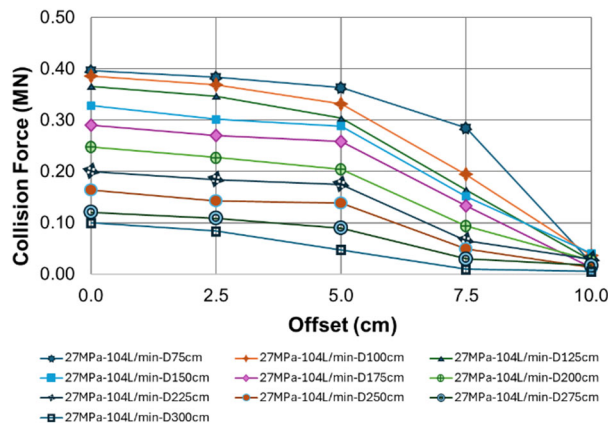


Figure 12. Jet impact force observation at the offset from the center.

4.3 Relationship between jet pressure and flow rate

In jet grouting, the applied pressure and flow rate are the major factors that control stream capability. The relationship between

the jet pressure and flow rate for a given nozzle diameter derived from Bernoulli's equation is provided in Equation (1).

$$P = 8\rho \left(\frac{Q}{\pi d^2} \right)^2 \quad (1)$$

Where: P = jet pressure
 ρ = fluid density
 Q = flow rate
 d = nozzle diameter

Figure 13 illustrates the relationship between jet pressure and flow rate for various nozzle types and diameters, as determined by Equation (1). As shown in Figure 13, if the nozzle area increases by a factor of 2 (i.e., two side nozzles), the flow rate must also be doubled to maintain the same pressure. Otherwise, the pressure will decrease by a factor of 4 if the flow rate remains unchanged. This relationship is crucial in optimizing nozzle design for jet injection systems since controlling nozzle size helps manage pressure and flow rate efficiency.

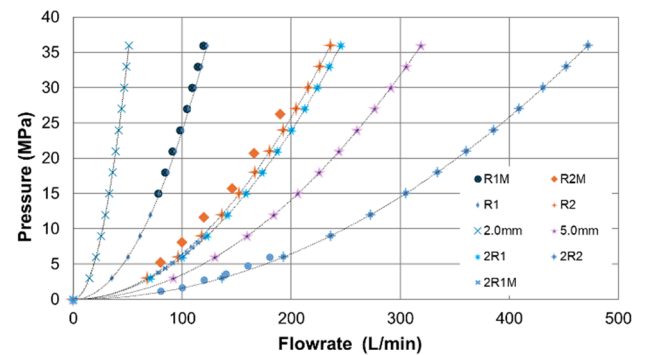


Figure 13. Correlation of applying pressure and flow rate by theory.

4.4 Indication of nozzle efficiency

The experimental data demonstrate that as the jet moves farther from the nozzle, impact force, velocity, and pressure gradually decrease, indicating a reduction in jet intensity. The quality of the nozzle plays an important role in the reduction of jet intensity (Wang, et al., 2021; Shen, et al., 2023). Therefore, nozzle efficiency checking is one of the most critical quality controls that leads to the key success of the jet grouting methods. The nozzle efficiency (η) can be analyzed using the attenuation coefficient (α) which indicates energy dissipation across varying flow rates and pressures.

The attenuation coefficient (α) is commonly used to characterize the attenuation rate of the maximum jet velocity (V_{xmax}) as a function of distance (x). Changes in the properties of the jetting fluid result in corresponding variations in the α value. Water or grout typically serves as a jetting fluid in jet grouting systems. Modoni et al. (2006) determined that for water jetting into a water medium, the attenuation coefficient (α) for water is approximately 16, based on laboratory experiments conducted by de Vleeshauer and Maertens (2000). Shibasaki (2003) also observed that the nozzle shape influences the attenuation of fluid velocity along the jet axis, which can be expressed as $\alpha = 16A$, where A represents a shape factor accounting for the nozzle geometry.

In this study, the attenuation coefficient was calculated using Equations (2) to (6). The attenuation coefficient was determined by following the principles presented in Rajaratnam (1976) and Croce, et al. (2014). A plot of the attenuation coefficient, expressed as the mean velocity (V_x/V_0), versus the scale distance (x/d_0) for various pressures and flow rates is provided in Figure 14. Figure 14 illustrates that despite changes

in the mean velocity and pressure, the general trend of energy attenuation remains similar for all conditions. This suggests that the jet stream's behavior follows a predictable pattern, which is crucial for understanding fluid dynamics and jet impact applications.

$$V_o = \frac{4Q}{n\pi d_o^2} \quad (2)$$

$$P_x = \frac{F_x}{A_{loadcell}} \quad (3)$$

$$\frac{V_x}{V_o} = \alpha \left(\frac{d_o}{x} \right) \quad (4)$$

$$\frac{V_x}{V_o} = \sqrt{\frac{P_x}{P_o}} \quad (5)$$

$$\alpha = \frac{x}{d_o} \left(\sqrt{\frac{P_x}{P_o}} \right) \quad (6)$$

Where: V_o = initial velocity at the nozzle
 V_x = velocity at a distance of x
 Q = flow rate
 d_o = nozzle diameter
 n = number of the nozzle
 P_o = jet pressure at the nozzle
 P_x = jet pressure at a distance of x = force from load cell (F_x) / area of load cell ($A_{loadcell}$)
 α = attenuation coefficient

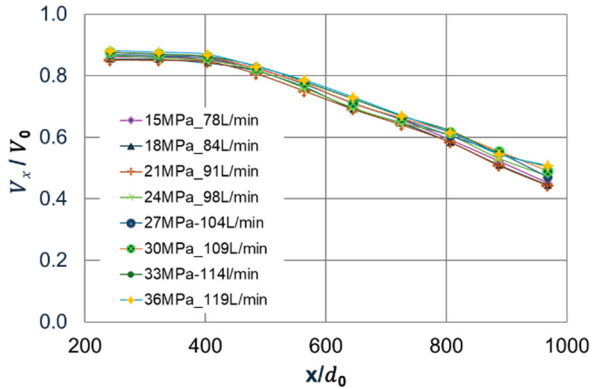


Figure 14. Plot of attenuation coefficient in the study.

The nozzle efficiency (η) was calculated by comparing the theoretical jet velocity (V_{ideal}) with the actual jet velocity (V_{actual}). The equations used to calculate the nozzle efficiency are shown in Equations (7) to (9).

$$V_{ideal} = \sqrt{\frac{2P}{\rho}} \quad (7)$$

$$V_{actual} = \frac{Q}{A_{nozzle}} \quad (8)$$

$$\eta = \frac{V_{actual}}{V_{ideal}} \times 100\% \quad (9)$$

The nozzle efficiency was checked on two nozzles (new and deteriorated nozzles). Tables 2 and 3 summarize the calculated nozzle efficiency values at various pressure and flow rate conditions for the new and deteriorated nozzles, respectively. Tables 2 and 3 indicate that the theoretical and actual jet

velocities continue to increase as the pressure increases. This is expected since higher pressure drives a higher exit velocity. However, in all cases, the exact velocity is slightly lower than the ideal velocity, indicating some energy losses due to friction, turbulence, and minor inefficiencies in the nozzle design.

Table 2. Summary of new nozzle efficiency computation.

Q (L/min)	P (MPa)	V_{ideal} (m/s)	V_{actual} (m/s)	η (%)
104	27	232.38	229.65	98.83
109	30	244.95	240.69	98.26
114	33	256.90	251.73	97.99
119	36	268.33	262.77	97.93

Table 3. Summary of deteriorated nozzle efficiency computation.

Q (L/min)	P (MPa)	V_{ideal} (m/s)	V_{actual} (m/s)	η (%)
106	27	232.38	206.56	88.89
111	30	244.95	216.30	88.30
116	33	256.90	226.04	87.99
121	36	268.33	235.79	87.87

Table 2 indicates that the new nozzle operates with high efficiency, ranging from 97.8% to 99.4% of the ideal velocity. The slight variations in efficiency may be due to slight variations in fluid turbulence flow or minor losses in the system. The computed results confirm that the nozzle under investigation exhibits excellent efficiency, with only minor deviations from the theoretical values. This suggests that the system is well-designed and capable of delivering high-performance fluid jetting with minimal losses.

Table 3 shows that the nozzle efficiency (η). The values for the deteriorated nozzle range from 87.8% to 88.8%, indicating noticeable efficiency losses compared to the data for the new nozzle. The results suggest that the nozzle indicates the presence of significant frictional losses or wear overtime, possibly due to prolonged usage, erosion, or obstruction. This would lead to increased energy dissipation, reducing the effectiveness of fluid jetting.

5 CONCLUSIONS AND RECOMMENDATIONS

This study evaluated the effectiveness of stream tests in assessing nozzle performance and fluid jet behavior for large-diameter jet grouting applications. Through systematic experimentation, key parameters were investigated, including nozzle condition (new versus deteriorated), injection pressure, flow rate, and observation distances both along the nozzle axis and laterally from the centerline. The following conclusions and recommendations are drawn.

- **Advantages of Air-Based Stream Testing:** Conducting stream tests in air offers distinct advantages over water-based testing. It is faster, more cost-effective, and operationally simpler, making it well-suited for routine field evaluations and on-site quality control.
- **Effective Jetting Boundary at the Epicenter:** The maximum jetting efficiency occurs along the nozzle's central axis. Efficiency significantly decreases with increasing lateral offset. At 10 cm from the centerline, the impact force was negligible, indicating minimal jetting effectiveness beyond this boundary.
- **Attenuation Behavior of Jet Power:** The reduction in jet impact force, velocity, and pressure with increasing distance was quantified using attenuation coefficients. For example, under a pressure of 33 MPa and a flow rate of

114 L/min, the attenuation coefficient was approximately 411, with corresponding velocity coefficients decreasing predictably from 0.88 to 0.50 across distances from 0.75 m to 3.00 m. These results support the development of predictive models for jet impact performance.

- **Pressure and Flow Rate Relationship:** The relationship between pressure and flow rate is highly dependent on nozzle diameter and configuration. The R2 nozzle demonstrated a greater jetting force but required approximately 40% more flow rate to maintain the same pressure. Understanding this relationship is essential for optimizing energy use and material delivery in grouting design.
- **Nozzle Efficiency Assessment:** Nozzle condition significantly influences jet performance. New nozzles achieved high efficiencies (97.4% - 99.5%), while deteriorated nozzles showed reduced performance (~87%), likely due to wear, erosion, or clogging. Comparing theoretical and actual jet velocities provides a practical metric for nozzle quality control.
- **Importance of Monitor Design:** In addition to the nozzle, the monitor structure plays a crucial role in maintaining consistent jetting performance. A well-designed monitor stabilizes flow, ensures accurate alignment, and minimizes pressure loss. Both nozzle and monitor must be evaluated together to provide optimal jetting results.
- **Practical Implications for Industry:** The stream test method provides a reliable and efficient approach for assessing the quality of jetting tools. Its practical application can enhance quality assurance protocols and reduce operational risks in large-diameter jet grouting projects.

Overall, the results of this stream test experiment demonstrated that nozzle size plays a crucial role in the performance of jet grouting, and its influence can be quantitatively assessed.

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